

CHEMICAL EFFECTS OF HIGHWAY RUNOFF ON THE  
SURFICIAL AQUIFER, BROWARD COUNTY, FLORIDA

By Barbara Howie and Bradley G. Waller

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## ABSTRACT

In many areas of Broward County, swales are commonly designed to accept stormwater runoff from highways. Two sites adjacent to heavily traveled highways were studied to determine if stormwater percolating through unsaturated sand underlying the swales may affect the quality of water in the Biscayne aquifer. Concentrations of selected chemicals common in highway runoff were measured in swale stormwater, in the unsaturated-zone percolate, and in the surficial aquifer during 12 storms, May through November 1983. Analyses of the unsaturated lithologic material at the two test sites and one control site were also made to indicate the extent of vertical attenuation of selected chemical constituents.

Results of trace metal and nutrient analyses indicated that there is no obvious water-quality effects on the surficial aquifer caused by highway runoff. In general, the data collected for dissolved trace metals indicated slight concentrations in stormwater samples with subsurface water samples usually indicating decreases in concentration below about 0.5 to 1 foot of unsaturated material. For most trace metals, the apparent decreases with depth were statistically significant based on nonparametric analysis of variance. Concentrations of dissolved nitrogen and phosphorus, however, were somewhat homogeneous and were not inferred to be significantly different with depth. Water hardness as calcium carbonate at both sites indicated a significant difference with depth because of calcium carbonate solution, but the effect of percolate hardness on the shallow ground water was negligible because of regional mixing.

The analyses of lithologic material at the two test sites indicated significant near-surface accumulation of some trace elements. For example, in the first foot below land surface, concentrations of iron, lead, and zinc were detected in the 1 to 7 milligrams per kilogram range, with concentrations decreasing sharply at lower depths. This near-surface accumulation was not indicated in the lithologic material at the control site.

## INTRODUCTION

Broward County is located on the southeast coast of Florida (fig. 1) and is underlain by the unconfined Biscayne aquifer. This surficial aquifer is the sole source of drinking water for most of southeast Florida. In Broward County, stormwater from roadways and other urban environments discharges directly to swales, drainage canals, French drains, or percolates directly to the shallow water table of the Biscayne aquifer. County and local concern regarding the potential for adverse effects caused by

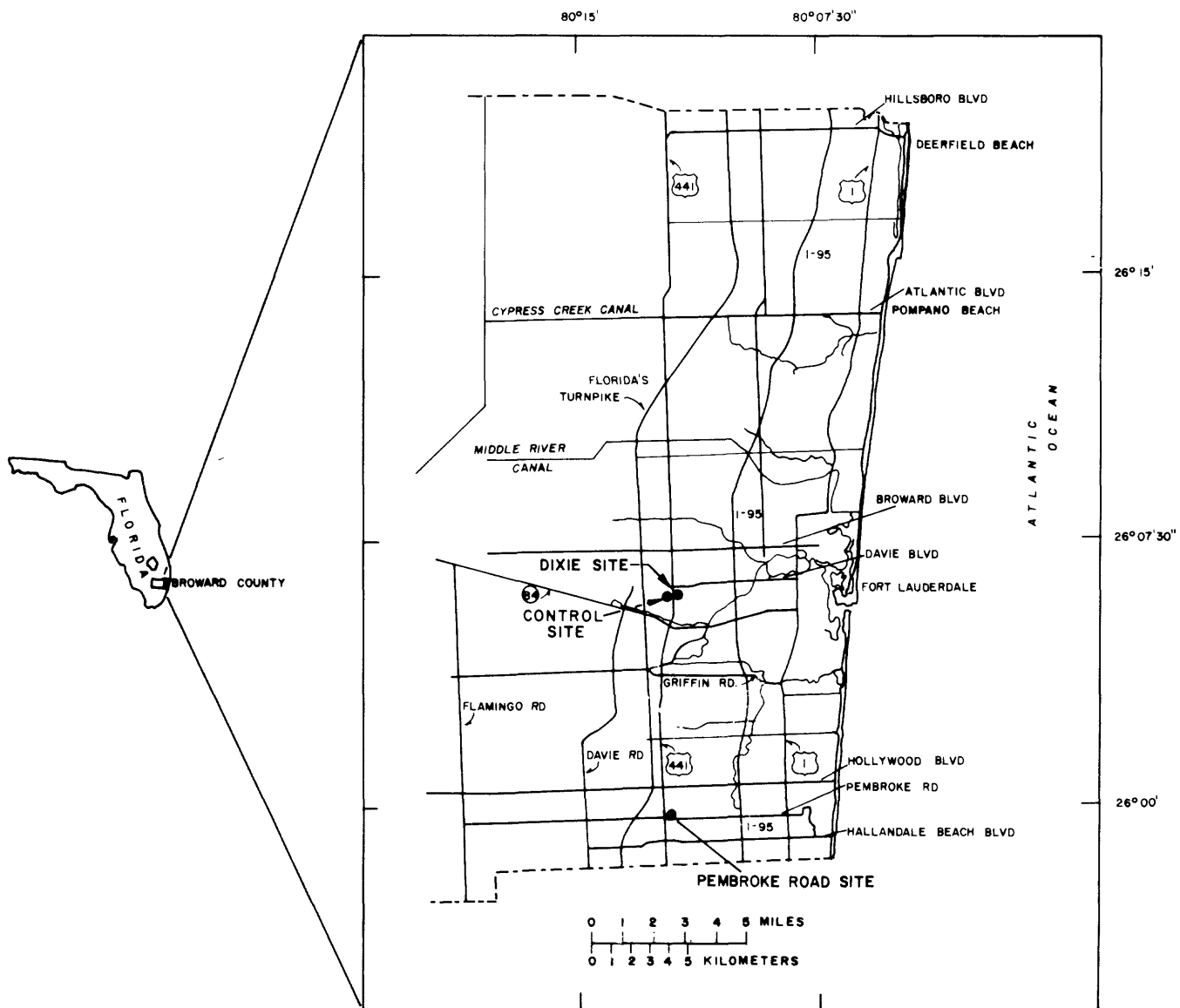


Figure 1.--Broward County, Fla., and test site locations.

uncontrolled stormwater recharge led to a recommendation for a water-quality-management plan for Broward County (Thomas Walker, Broward County Water Resources Management Division, oral commun., 1983). The management plan proposed to take advantage of the moderate permeability of the surficial sand in Broward County and to use vegetated swale areas as a disposal method for excess stormwater. Vegetated swales would reduce the rate of stormwater percolation to ground water more than would direct discharge to canals by way of sewers or by disposal on unvegetated surfaces. Many potential urban contaminants also would be removed by plant assimilation, filtering, and sorption by the surficial soils, or geochemical interactions with surficial materials. Data on the effects of vegetated swales and unsaturated surficial materials on the quality of stormwater recharge, however, are sparse.

A recent study of the effects of highway runoff on shallow subsurface water in Dade County (Waller and others, 1984) reported that certain traffic-generated contaminants are filtered or absorbed within a vegetated swale and unsaturated limestone. The present study described here assesses the chemical impacts of highway runoff on shallow subsurface water at two vegetated swale sites overlying unsaturated sand in Broward County and is intended as a companion report to the Dade County investigation.

### Purpose and Scope

The purpose of this investigation was to determine the quality of highway runoff and to assess its effects on the distribution of selected chemical constituents contained in the water of the unsaturated and saturated zones of the surficial aquifer. These data provide insight into the relative magnitude of chemical attenuation which occurs in stormwater percolate (infiltrate) in unsaturated sand under a vegetated swale. The scope of the study included chemical analyses of lithologic material at two test sites and one control site, and chemical analyses of stormwater runoff collected from the swale, water from the unsaturated zone, and water from the saturated zone underneath the swale at two test sites. The period of study was May through November 1983. The chemical constituents selected as tracers were lead, zinc, iron, cadmium, chromium, nickel, mercury, nitrogen, and phosphorus. These constituents are commonly used as gross indicators of urban contamination.

This report presents the results of data primarily analyzed using analysis of variance techniques. A complete listing of the results of chemical analyses also is presented.

### Acknowledgments

The authors wish to thank the staffs of the city of Fort Lauderdale, Broward County, and the State Department of Transportation for their permission to install hydrologic stations and instrumentation on their property. Thomas D. Walker of the Broward County Water Resources Management Division provided information on roadway history and traffic counts. Appreciation also is extended to the Broward County Commission for their support of this investigation.

## DESCRIPTION OF SITES

The Dixie water-treatment plant site (fig. 2), referred to as Dixie plant, is adjacent to U.S. Highway 441 (State Road 7) which is one of the heaviest traveled roadways in Broward County (39,000 vehicles per day according to the Florida Department of Transportation data, 1982). In the 1920's, the roadway consisted of two lanes, but in 1963 it was expanded to four lanes plus a left-turning lane. The swale area, which receives stormwater runoff, is adjacent to the pavement and is partially vegetated. The land-surface elevation at this site is about 15 feet above sea level, and the thickness of the unsaturated zone ranges from 12 to 13 feet.

The Pembroke Road site (fig. 3) is adjacent to the southeast corner of the intersection of Pembroke Road and U.S. Highway 441. Pembroke Road is a major east-west artery in south Broward County with a traffic load of 20,000 vehicles per day according to the Florida Department of Transportation. A vegetated swale area receives stormwater runoff from both the two eastbound lanes of Pembroke Road and from the entrance lane from northbound U.S. Highway 441. Elevation of the land surface is about 10 feet above sea level, and the thickness of the unsaturated zone ranges from 7 to 8 feet.

The unsaturated zone at both the Dixie plant and Pembroke Road test sites primarily consists of sand and generally is representative of the surficial material throughout the eastern part of Broward County (table 1). These surficial sands are clean and moderately permeable, allowing moderate vertical percolation of stormwater.

The control (background) site is located in an undeveloped area about 0.5 mile west of the Dixie water-treatment plant (fig. 1). The area is sparsely vegetated with weeds. Elevation of this site is about 15 feet above sea level, and the unsaturated zone is greater than 15 feet thick as a result of pumpage from the Dixie well field. The nearest roadway is a lightly traveled residential street located 200 feet from the site. The control site does not have a swale or catchment area; thus, the only effects from vehicular traffic would be limited to atmospheric deposition.

## METHODS OF STUDY

### Data Collection

Samples of the surficial material at varying depths were collected for lithologic description and chemical analysis at the Dixie plant and Pembroke Road test sites and at the control site. Each site was cored without circulating fluids, using a 3.5-inch diameter drilling spoon. Sampling intervals from the surface were 0.5-foot composites from about 0 to 0.5-foot, 1.0-foot, and thereafter at about 1-foot intervals to the water table. Samples of surface materials (0-0.05 foot) in the swale also were collected. Samples were shipped to the U.S. Geological Survey Central Laboratory in Doraville, Ga., for chemical analysis.

Samples of stormwater runoff in the swale, stormwater percolate in the unsaturated zones, and water from the water-table aquifer were collected only at the two test sites. A generalized schematic of the sampling installations at Dixie plant and Pembroke Road are shown in figure 4. A continuous recording rain gage installed at the Pembroke Road site and the National Weather Service rainfall station at the Dixie water-treatment plant (Fort Lauderdale) were used to collect rainfall data.

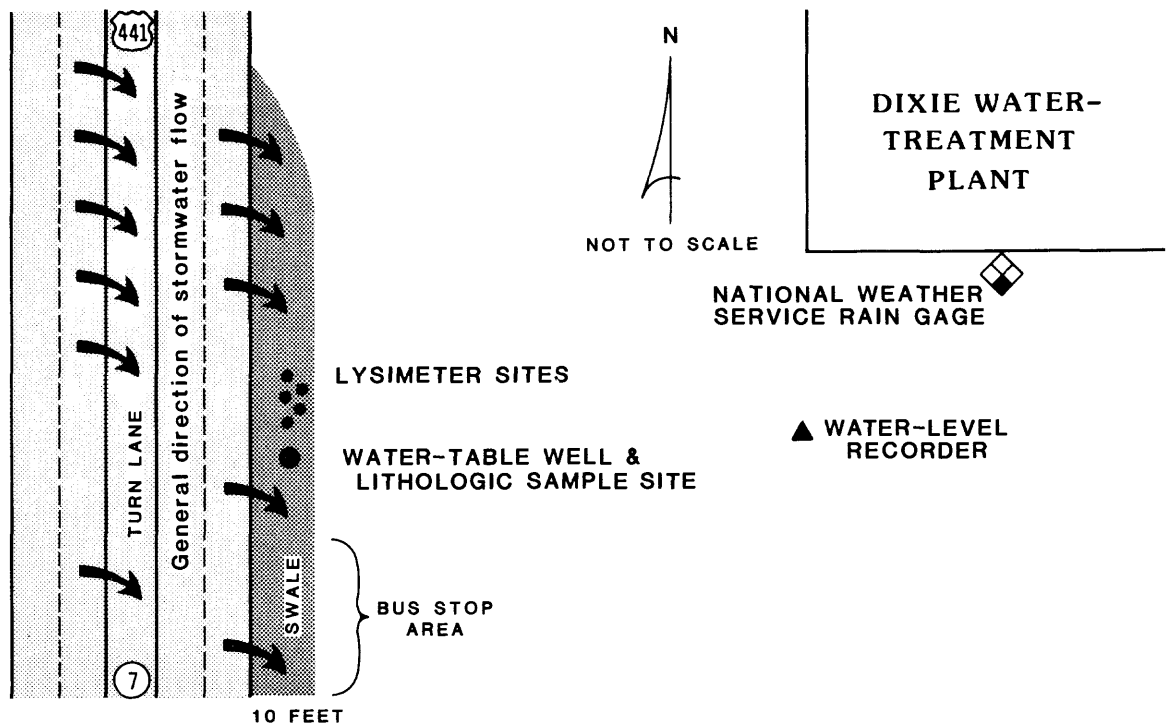


Figure 2.--Dixie water-treatment plant test site showing sampling locations.

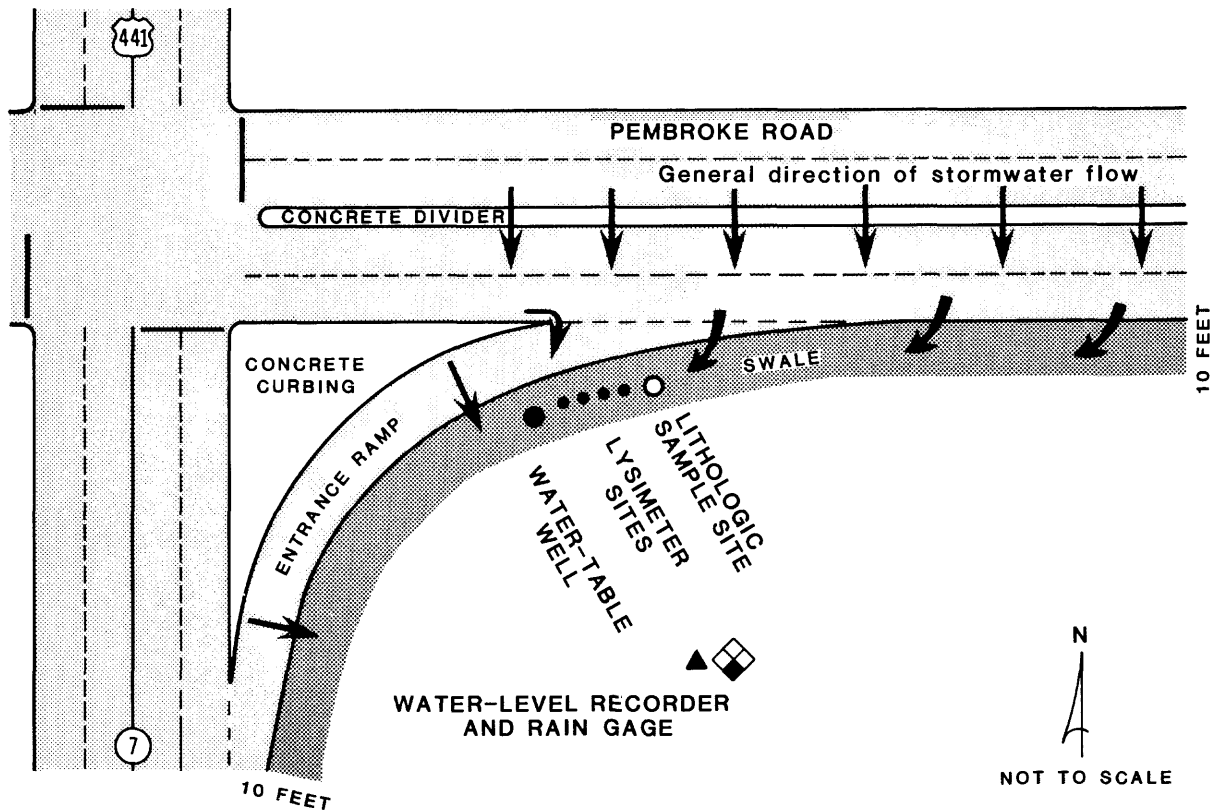
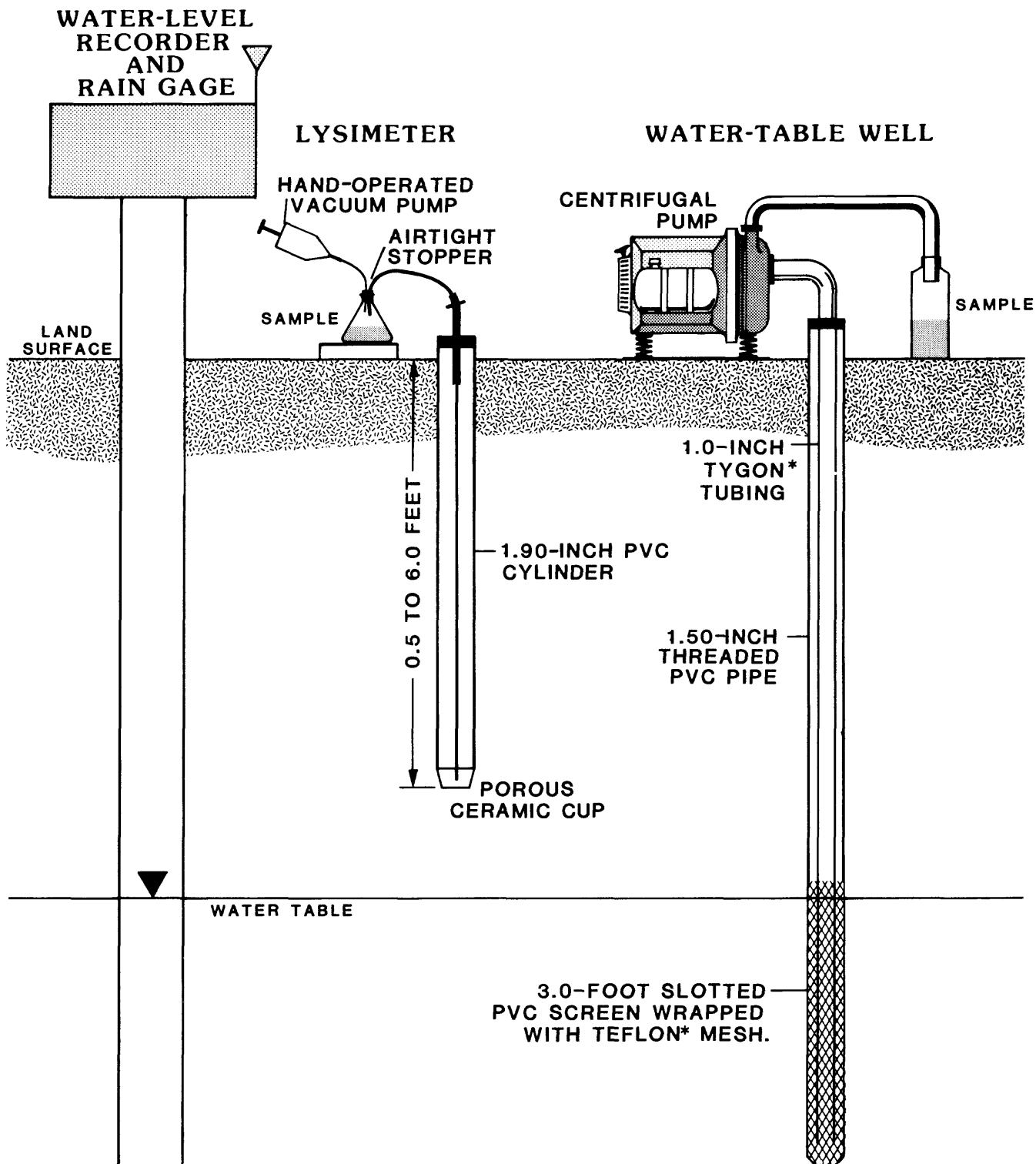


Figure 3.--Pembroke Road test site showing sampling locations.



Table 1.--Lithologic log of test holes at the Dixie water-treatment plant  
and Pembroke Road sampling sites

Depth below land surface (feet)	Lithologic description
Dixie water-treatment plant	
0.0-0.5	Sand, brownish-gray (5 YR 4/1) to olive-gray (5 Y 4/1), very fine to coarse, subrounded to subangular, moderately to poorly sorted, quartz grains partially coated with calcium carbonate, silty in parts, trace root material, mixed with abundant limestone fragments (fine material).
0.5-4.0	Sand, brownish gray (5 YR 4/1) to olive-gray (5 Y 4/1), fine to medium with occasional coarse, subrounded to subangular, moderately sorted, slight calcium carbonate coating on quartz grains, trace of limestone fragments (possible fill material).
4.0-4.5	Sand, pale-yellowish-brown (10 YR 6/2), quartz, fine to medium, occasional coarse, subrounded to subangular, moderately sorted, noncalcareous, "clean" (very low percent of accessory minerals).
4.5-5.5	Sand, pinkish-gray (5 YR 8/1), quartz, fine to medium, subangular, well sorted, very "clean."
5.5-8.0	Sand, very light-gray (N 8) to pinkish-gray (5 YR 8/1), fine to medium quartz grains, mostly subangular, well sorted, very "clean."
8.0-8.5	Sand, dusky-brown (5 YR 2/2), tinted-yellow quartz grains, fine to medium, occasional coarse, subrounded, moderately to poorly sorted, silty, iron stained.
8.5-10.0	Sand, grayish-brown (5 YR 3/2), fine to medium, occasional coarse quartz grains, predominantly subrounded, moderately well sorted, very slightly silty, iron stained.
Pembroke Road	
0.0-0.5	Top soil, dark-gray (N 3), mixed with about 10 percent fine to coarse quartz and carbonate sand, with abundant root material.
0.5-4.5	Fill, mostly fine to medium, subrounded, moderately to well sorted quartz sand with occasional limestone fragments.
4.5-5.5	Sandstone, very pale orange (10 YR 8/2) to grayish-orange (10 YR 7/4), friable, crumbly, quartz grains, very fine to medium, subangular to subrounded, moderately sorted, calcareous cement, with occasional clusters of fine to medium calcite crystals, visible porosity--very good.
5.5-9.0	Sand, very pale orange (10 YR 8/2) to yellowish-gray (5 Y 7/2), quartz, fine to medium, subrounded, well sorted, trace shell fragments, interbedded with very thin crumbly sandstone layers.
9.0-10.0	Sand, very pale orange (10 YR 8/2), very fine to medium, subrounded, very well sorted.



\*Use of Teflon and Tygon in this report are for identification purposes and does not constitute endorsement by the U.S. Geological Survey.

Figure 4.--Installed lysimeter, water-table well, and sampling apparatus.

Stormwater samples were collected from swales by grab sample, from the unsaturated zone by lysimeters, and from the water-table aquifer from wells. Lysimeters consisting of a standard 1- to 2-micron porous ceramic cup at the end of a 1.9-inch PVC (polyvinyl chloride) tube (fig. 4) were installed at 0.5, 1.0, 2.0, and 6.0 feet below land surface at both sampling sites. An additional lysimeter was installed at a depth of 3.0 feet at the Dixie plant. Lysimeters were installed tightly into cored holes and packed at the surface with a bentonite powder. Lysimeters were evacuated by applying a 50-lb/in<sup>2</sup> vacuum at the beginning of each storm and samples were collected by aspirating lysimeters after a 20- to 24-hour period. Variable sample volumes collected in lysimeters often prevented complete analytical coverage for many storms. Wells tapping the water-table aquifer were installed 2 to 3 feet below the water table and double screened. Water samples were collected from the water-table wells by using either a centrifugal or peristaltic pump, depending upon the pumping rate and altitude of the water-table surface.

Runoff samples were collected at the two test sites following different rainfall amounts and different antecedent dry periods so data would be representative of south Florida's varied rainfall. Most swale samples were collected within 2 hours of the start of rainfall for each event. For the first 10 storms, highway runoff samples from the swale and water table, except nutrients for the first storm, were filtered through a 0.45-micron filter, so that data were generally comparable both with data from the lysimeters in which the ceramic cup acts as a filter, and with the data from the Dade County study (Waller and others, 1984). Some unfiltered samples of highway runoff from the last two storms were collected from the swales and wells. All water samples were treated in the field and shipped to the U.S. Geological Survey laboratories in Doraville, Ga., or Ocala, Fla., for chemical analysis.

In addition to mechanical filtering, it is noted that lysimeters may affect the quality of water samples by such processes as sorption and desorption. The effect of lysimeters altering the concentrations of trace metals, major ions, and nutrients in water samples has been studied by several researchers. Johnson and others (1981) suggested that the lysimeters do not alter the concentrations of trace metals or major ions. Hansen and Harris (1975) examined the effect of lysimeters on nitrates and phosphates at concentrations that were comparable to those observed in this investigation, and concluded that lysimeters may introduce bias into nutrient data because of sorption or desorption. Hansen and Harris (1975) suggested that potential bias is increased when the "sorptive capacity of the ceramic cup is significantly greater than that of the adjacent soil," as may be the case at the test sites.

### Approach

The two categories of common highway contaminants investigated in this study were the trace metals (cadmium, chromium, copper, iron, lead, mercury, nickel, and zinc) and the primary nutrients (organic nitrogen, ammonia, nitrite, nitrate, and phosphate). In stormwater runoff, these particular trace metals are often the byproducts of the wearing of vehicle chassis, tires and road surfaces, roadway maintenance, street litter, and fuel and oil additives (Gupta and others, 1981, p. 3-5). Nutrients in stormwater runoff are mainly derived from fertilizers applied to the area drained by the swale (Gupta and others, 1981, p. 4).

The general approach to estimating the chemical impacts of highway runoff on the surficial subsurface water was to determine the vertical distribution of these common tracer constituents in the lithologic material and surface and subsurface water. The multiplicity of data gathered during this investigation, as factors of storm characteristics, depth, and site, necessitated considerable reliance on statistical methods of analysis throughout the following discussion.

The principal method of statistical analyses was a two-way factorial analysis of variance (ANOVA). Data for each constituent was ranked prior to ANOVA tests to adjust for nonnormal distribution as described in Helsel (1983). Data reported below detection limits also were included in the ranking prior to ANOVA tests.

### CHEMICAL CONSTITUENTS IN UNSATURATED SAND

Chemical analyses of lithologic material collected at varying depths indicated several constituents were in noticeably greater concentrations at or near the land surface at the Dixie plant and Pembroke Road test sites (tables 2, 3, and 4). At the control site, vertical variations in concentrations were not conspicuous. The vertical differences in concentrations of such constituents as iron, lead, and zinc between the two test sites and the control site strongly suggest a chemical loading and attenuation in the near-surface lithology at the two test sites.

Table 2.--Chemical analysis of lithologic samples at varying depth intervals at the Dixie water-treatment plant

[ $\mu\text{g/kg}$  = microgram per kilogram;  $\text{g/kg}$  = gram per kilogram;  $\text{mg/kg}$  = milligram per kilogram;  
 < = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface							
	0.0-0.05 (swale)	0.0-0.5	0.5-1.0	1.5-2.0	2.5-3.0	3.5-4.0	4.5-5.0	5.5-6.0
Cadmium, $\mu\text{g/kg}$	<1	3	3	3	<1	2	2	2
Chromium, $\mu\text{g/kg}$	20	9	9	3	4	4	2	4
Copper, $\mu\text{g/kg}$	3	10	9	<1	<1	<1	<1	<1
Iron, $\mu\text{g/kg}$	1,200	490	340	29	26	25	17	17
Lead, $\mu\text{g/kg}$	1,000	1,400	290	<10	<10	<10	<10	<10
Manganese, $\mu\text{g/kg}$	26	13	12	1	1	1	<1	<1
Mercury, $\mu\text{g/kg}$	.05	.01	.03	.01	<.01	.01	<.01	<.01
Nickel, $\mu\text{g/kg}$	<10	<10	<10	<10	<10	<10	<10	<10
Zinc, $\mu\text{g/kg}$	170	90	47	6	2	2	4	2
Inorganic carbon, $\text{g/kg}$	25	16	25	3.7	2.7	4.2	.3	<.1
Organic carbon, $\text{g/kg}$	--	10	9	1.3	1.6	.1	.2	--
Nitrogen, ammonia plus organic, $\text{mg/kg}$	2,000	1,200	900	120	80	70	30	20
Nitrogen, nitrite plus nitrate, $\text{mg/kg}$	4	3	<2	<2	<2	5	<2	<2
Nitrogen, ammonia, $\text{mg/kg}$	3.2	1	1.2	.4	.4	1.3	.4	<.4
Phosphorus, $\text{mg/kg}$	8	48	2	19	5	8	34	2

Table 3.--Chemical analysis of composite lithologic samples at varying depth intervals at Pembroke Road

[ $\mu\text{g/kg}$  = microgram per kilogram;  $\text{g/kg}$  = gram per kilogram;  $\text{mg/kg}$  = milligram per kilogram; < = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface					
	0.0-0.05 (swale)	0.0-0.5	0.5-1.0	1.5-2.0	2.5-3.0	5.0-6.0
Cadmium, $\mu\text{g/kg}$	10	4	3	2	2	2
Chromium, $\mu\text{g/kg}$	40	10	6	2	5	4
Copper, $\mu\text{g/kg}$	100	10	2	<1	<1	1
Iron, $\mu\text{g/kg}$	2,400	490	64	22	26	27
Lead, $\mu\text{g/kg}$	6,600	2,500	40	<10	<10	20
Manganese, $\mu\text{g/kg}$	99	24	4	<1	<1	1
Mercury, $\mu\text{g/kg}$	.53	.05	<.01	<.01	.01	<.01
Nickel, $\mu\text{g/kg}$	30	10	<10	<10	<10	<10
Zinc, $\mu\text{g/kg}$	1,800	280	39	1	3	1
Inorganic carbon, $\text{g/kg}$	41	28	7.0	.6	1.3	15
Organic carbon, $\text{g/kg}$	249	38	3.0	1.5	.7	0
Nitrogen, ammonia plus organic, $\text{mg/kg}$	23,000	3,700	530	130	140	150
Nitrogen, nitrite plus nitrate, $\text{mg/kg}$	76	9	2	3	<2	<2
Nitrogen, ammonia, $\text{mg/kg}$	2.4	5.6	2.5	2.9	1.9	1.9
Phosphorus, $\text{mg/kg}$	78	23	8	2	9	11

ANOVA was performed to test the effect of depth using the analytical results of the upper and lower lithologic material at the two test sites (Dixie plant and Pembroke Road) and the control site near Dixie Plant. The data set for the upper material included the analytical results of the swale scrapings and the lithologic sample of the interval from land surface to 0.5 foot; the data set for the lower material included the analyses of all samples of the intervals from 0.5 to 6 feet below land surface. Results of the ANOVA are given in table 5.

A significant difference in concentrations of the upper and lower material (5-percent significance level) was indicated for most constituents. Only cadmium, ammonia nitrogen, and phosphorus, by depth, did not exceed the critical level of the test. Concentrations for virtually all constituents at the test sites were notably greater in the upper material (0-0.5 feet); however, the greater concentrations at the control site often occurred in the lower material.

Analytical results of the lithologic material for all depths also were tested to determine if significant differences were inferred among the three sites. ANOVA results (table 5) inferred that only nickel, ammonia nitrogen, and phosphorus concentrations were significantly different among sites. ANOVA results of nickel were greatly affected by the high near-surface concentrations at Pembroke Road, whereas ammonia, nitrogen, and phosphorus results were

Table 4.--Chemical analysis of composite lithologic samples at varying depth intervals  
at the control site

[ $\mu\text{g/kg}$  = microgram per kilogram;  $\text{g/kg}$  = gram per kilogram;  $\text{mg/kg}$  = milligram per kilogram;  
< = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface						
	0.0-0.05	0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.5-3.0	5.5-6.0
Cadmium, $\mu\text{g/kg}$	<1	<1	<1	<1	2	5	3
Chromium, $\mu\text{g/kg}$	8	8	9	5	7	4	7
Copper, $\mu\text{g/kg}$	<1	<1	<1	<1	<1	3	1
Iron, $\mu\text{g/kg}$	40	9	22	13	260	88	86
Lead, $\mu\text{g/kg}$	10	<10	<10	<10	10	40	20
Manganese, $\mu\text{g/kg}$	2	<1	1	<1	2	4	3
Mercury, $\mu\text{g/kg}$	<.01	<.01	<.01	<.01	.01	.01	<.01
Nickel, $\mu\text{g/kg}$	<10	<10	<10	<10	<10	10	<10
Zinc, $\mu\text{g/kg}$	6	24	6	4	4	5	6
Inorganic carbon, $\text{g/kg}$	.4	.2	2.9	7.7	17	57	31
Organic carbon, $\text{g/kg}$	3.1	1.0	2.9	36	3.0	4.0	0
Nitrogen, ammonia plus organic, $\text{mg/kg}$	1,500	140	970	270	720	730	270
Nitrogen, nitrite plus nitrate, $\text{mg/kg}$	<2	<2	<2	<2	<2	<2	<2
Nitrogen, ammonia, $\text{mg/kg}$	3.7	4.9	4.7	2.8	8.6	4.6	6.7
Phosphorus, $\text{mg/kg}$	24	50	39	217	36	70	36

Table 5.--Analysis of variance on ranks in lithologic samples at the three sites  
[P-level, the probability that observed differences are due to chance rather  
than to the tested effect]

Dixie plant, Pembroke Road, and control sites			Dixie plant, Pembroke Road, and control sites		
Constituent	Effects		Constituent	Effects	
	Site	Depth		Site	Depth
Cadmium	0.187	0.961	Mercury	.212	1.042
Chromium	.459	1.0004	Nickel	1.039	1.030
Copper	.164	1.020	Zinc	.986	1.0008
Iron	.499	1.033	Nitrogen, organic	1.070	1.0006
Lead	.106	1.010	Nitrogen, ammonia	1.0001	.082
Manganese	.793	1.015	Phosphorus	1.003	.070

<sup>1</sup>Effects significant at the 0.05 probability level.

affected by the generally greater and homogeneous concentrations at the control site. Overall, however, concentrations of most constituents were usually greater at the test sites, primarily Pembroke Road.

The analytical results of this study were compared with lithologic data collected during a similar study in Dade County (Waller and others, 1984), five constituents (iron, lead, zinc, kjeldahl nitrogen, and phosphorus) were examined using ANOVA. ANOVA tests inferred that lead and zinc were not different among the two tests in Broward and the test site in Dade County. Iron, however, was significantly different and was attributed to the generally greater iron concentrations throughout the lithologic vertical in the Dade County limestone. Both kjeldahl nitrogen and phosphorus were significantly different among the Broward and Dade County test sites. As with iron, greater concentrations of kjeldahl nitrogen and phosphorus were present throughout the lithologic vertical in the Dade County sample. Phosphorus was also notably greater in the surface material at the Dade test site, although surface kjeldahl nitrogen was much greater at the Pembroke Road test site in Broward County.

#### Chemical Constituents in Water Samples of Highway Runoff and the Surficial Aquifer

Twelve storms were sampled within about 2 hours following the start of each event. The storms sampled at the two sites represent a rather wide range of meteorological conditions (table 6). For example, storms 1, 5, and 10 through 12 represent stormwater conditions following extended dry periods; storms 4 and 6 represent stormwater conditions after 24 hours of almost continuous rainfall. The rise in water level during each storm, except storms 5 and 11, indicated stormwater percolation to the surficial aquifer. However, a cursory assessment indicated that the water-level rise at Pembroke was significantly related to rainfall, but not at Dixie plant. Regression analyses inferred that about 80 to 90 percent of the rise in shallow ground water at Pembroke during an event was explained by rainfall, but only about 20 to 40 percent was explained at the Dixie plant. Pumping at the nearby Dixie well field, and greater thickness of unsaturated material at the Dixie plant (12-13 feet) than at Pembroke Road (7-8 feet), were likely factors masking a simple relation at the Dixie plant. Interestingly, antecedent conditions were not indicated as significant effects in water-level relations at either test site; however, these data were not evaluated in detail.

A summary of the concentrations of dissolved trace metals, nitrogen, and phosphorus detected in samples of swale stormwater and shallow ground water at the two test sites for the 12 storms is given in tables 7 and 8. For the most part, the concentrations of dissolved trace metals were low with most very near or below the limit of analytical detection. Only dissolved chromium, iron, nickel, and zinc were consistently detected in quantifiable concentrations throughout the monitoring period. It is noted, however, that the analytical detection level of the method used for dissolved copper and lead was 10  $\mu\text{g/L}$ , and, therefore, less definitive than the 1  $\mu\text{g/L}$  level used for the other metals. Nitrogen concentrations were notably greater in samples of stormwater in the swales than in the respective ground water. Most of the nitrogen was in the organic fraction. Concentrations of phosphorus were also generally greater in swale samples.

Table 6.--Summary of hydrologic conditions at the two test sites for each sampling event

Site	Storm	Date	Rainfall (inches)	Water level rise (feet)	Cumulative antecedent rainfall (inches)				
					1 day	3 days	7 days	14 days	30 days
Dixie plant	1	05/26/83	0.11	0.27	0.00	0.00	0.01	0.73	0.79
Pembroke Road			.08	.02	.00	.00	.00	.36	--
Dixie plant	2	06/01/83	.33	.33	.77	1.10	2.48	2.49	3.24
Pembroke Road			3.46	1.28	2.74	3.46	3.54	3.54	3.90
Dixie plant	3	06/08/83	1.10	.12	.00	.16	3.31	5.79	6.52
Pembroke Road			1.30	.22	.00	.00	5.21	8.75	9.11
Dixie plant	4	06/09/83	2.50	.49	1.10	1.19	4.08	6.89	7.62
Pembroke Road			2.60	1.18	1.30	1.30	3.05	10.05	10.41
Dixie plant	5	07/27/83	.12	.00	.00	.00	.35	.35	.49
Pembroke Road			.07	.00	.00	.00	.00	.00	.38
Dixie plant	6	07/28/83	1.16	.42	.12	.12	.47	.47	.61
Pembroke Road			1.33	.37	.07	.07	.07	.07	.45
Dixie plant	7	08/23/83	.78	.31	.00	.03	.29	3.47	8.80
Pembroke Road			2.41	.60	.00	.00	.46	1.52	6.09
Dixie plant	8	09/01/83	.86	.30	.98	2.26	3.32	4.15	8.75
Pembroke Road			1.49	.61	.00	1.24	1.39	4.91	6.85
Dixie plant	9	09/28/83	.42	.13	.30	.73	2.74	3.57	9.37
Pembroke Road			.23	.10	.17	1.14	2.81	3.07	5.86
Dixie plant	10	11/03/83	1.03	.20	.00	.01	.01	3.08	6.85
Pembroke Road			Trace						
Dixie plant	11	11/16/83	.37	.00	.00	.00	.04	1.44	4.54
Pembroke Road			Trace						
Dixie plant	12	11/30/83	0						
Pembroke Road			2.10	.28	.00	.00	.00	.15	.71

Results of the limited sampling of total recoverable concentrations of trace metals (table 7, storms 11 and 12) and nitrogen and phosphorus (table 8, storms 11 and 12) suggest general increases above dissolved concentrations. Also, total concentrations of cadmium (20  $\mu\text{g/L}$  at both sites) and lead (200-300  $\mu\text{g/L}$ ) were greater than usually found in water samples from the Biscayne aquifer. For example, in a study of raw water from 12 public supply wells, Irwin and Healy (1978) found concentrations of <1 to 7  $\mu\text{g/L}$  of cadmium and 4 to 45  $\mu\text{g/L}$  of lead. However, lack of data for total recoverable analyses for the tracer constituents precludes assessment of apparent differences.



Table 7.--Trace metal concentrations in highway runoff from swales and in shallow ground water  
at the two test sites

[Metal concentrations are dissolved in micrograms per liter unless otherwise noted. S =  
swale; GW = shallow ground water; < = concentration below analytical detection limit;  
-- = no data]

Storm	Site	Sampling point	Metal concentrations							
			Cadmium	Chromium	Copper	Iron	Lead	Mercury	Nickel	Zinc
1	Dixie plant	S	<1	1	10	7	<10	<0.1	4	8
		GW	<1	3	<10	92	<10	<.1	3	4
	Pembroke Road	S	2	2	40	160	<10	.4	12	400
		GW	<1	12	<10	64	<10	<.1	2	4
2	Dixie plant	S	<1	2	10	60	<10	<.1	5	9
		GW	<1	2	<10	100	<10	.1	1	14
	Pembroke Road	S	<1	--	<10	61	<10	--	--	<3
		GW	1	9	<10	23	<10	<.1	5	11
4	Dixie plant	S	--	--	--	--	--	--	--	--
		GW	<1	9	<10	30	<10	<.1	2	17
	Pembroke Road	S	--	--	--	--	--	--	--	--
		GW	<1	8	<10	14	<10	<.1	3	<3
5	Dixie plant	S	<1	8	<10	39	<10	<.1	1	4
		GW	--	--	--	--	--	--	2	--
	Pembroke Road	S	<1	2	<10	5	<10	.4	13	<3
		GW	<1	1	<10	5	<10	<.1	1	5
6	Dixie plant	S	<1	3	20	35	<10	<.1	3	48
		GW	<1	9	<10	12	<10	<.1	2	22
	Pembroke Road	S	<1	3	<10	66	<10	<.1	1	17
		GW	<1	2	<10	5	<10	<.1	1	<3
7	Dixie plant	S	<1	6	10	46	<10	<.1	2	25
		GW	<1	--	<10	140	<10	.1	1	9
	Pembroke Road	S	<1	8	<10	84	40	<.1	1	35
		GW	<1	--	<10	42	<10	<.1	2	5
8	Dixie plant	S	<1	<1	<10	28	<10	<.1	3	31
		GW	<1	<1	<10	67	<10	.1	1	7
	Pembroke Road	S	<1	<1	<10	72	20	<.1	1	50
		GW	<1	<1	<10	58	<10	<.1	1	34
9	Dixie plant	S	<1	<1	<10	36	10	<.1	2	6
		GW	<1	<1	<10	84	<10	<.1	<1	<3
	Pembroke Road	S	<1	18	<10	25	30	<.1	1	12
		GW	<1	<1	<10	38	<10	<.1	1	<3
11	Dixie plant	S	1	<10	13	40	28	<0.1	1	30
		GW	<1	<10	1	110	<1	<.1	<1	20
	Pembroke Road	S	--	--	--	--	--	--	--	--
		GW	--	--	--	--	--	--	--	--
11 <sup>1</sup>	Dixie plant	S	40	150	100	4,800	2,100	<.1	8	580
		GW	20	20	40	780	200	<.1	1	10
	Pembroke Road	S	--	--	--	--	--	--	--	--
		GW	--	--	--	--	--	--	--	--
12 <sup>1</sup>	Dixie plant	S	--	--	--	--	--	--	--	--
		GW	--	--	--	--	--	--	--	--
	Pembroke Road	S	30	40	50	4,300	1,800	<.1	12	780
		GW	20	10	20	630	300	<.1	2	10

<sup>1</sup>Concentrations are total recoverable in micrograms per liter.

Table 8.--Nitrogen and phosphorus concentrations in highway runoff from swales and in shallow ground water at the two test sites

[Concentrations are dissolved in milligrams per liter unless otherwise noted. S = swale; GW = shallow ground water; < = concentration below analytical detection limit; and -- = no data]

Storm	Site	Sampling point	Concentrations			
			Total nitrogen	Kjeldahl nitrogen	Nitrate	Total phosphorus
1	Dixie plant	S	3.2	2.5	.65	0.28
		GW	.27	.21	.04	.05
	Pembroke Road	S	6.92	5.12	1.70	.56
		GW	.47	.28	.18	.03
2	Dixie plant	S	1.1	1.08	<.01	.10
		GW	.37	.32	.04	.03
	Pembroke Road	S	1.50	1.05	.43	.11
		GW	1.02	.41	.60	.02
3	Dixie plant	S	.73	.48	.21	.07
		GW	--	--	--	--
	Pembroke Road	S	.88	.63	.19	.05
		GW	--	--	--	--
7	Dixie plant	S	.51	.25	.24	.10
		GW	.66	.21	.41	.04
	Pembroke Road	S	.50	.40	.09	.08
		GW	.73	.19	.53	.03
8	Dixie plant	S	.38	<.22	.12	.03
		GW	3.75	.45	3.25	.03
	Pembroke Road	S	.34	.22	.09	.03
		GW	.45	.14	.30	.01
9	Dixie plant	S	.73	.32	.39	.02
		GW	3.49	.49	2.96	.03
	Pembroke Road	S	.59	.32	.26	.02
		GW	.52	.20	.31	.01
10	Dixie plant	S	.55	.54	.01	.02
		GW	.96	.23	.68	.03
	Pembroke Road	S	--	--	--	--
		GW	--	--	--	--
11	Dixie plant	S	.99	.57	.37	.08
		GW	.83	.22	.57	.02
	Pembroke Road	S	--	--	--	--
		GW	--	--	--	--
11 <sup>1</sup>	Dixie plant	S	1.96	1.50	.39	.30
		GW	.86	.24	.57	.02
	Pembroke Road	S	--	--	--	--
		GW	--	--	--	--
12 <sup>1</sup>	Dixie plant	S	--	--	--	--
		GW	--	--	--	--
	Pembroke Road	S	4.32	3.60	.62	.17
		GW	.30	.12	.18	.04

<sup>1</sup>Concentrations are total recoverable in micrograms per liter.

ANOVA was used in the attempt to assess statistically the distribution of the various tracer constituents at the two test sites. The selected data given in tables 7 and 8 along with the data for the unsaturated-zone percolate (Supplementary Data, page 20) were used for the analysis. Only those dissolved metals with data sets having a majority of positive detections were used for the ANOVA tests. As with the lithologic data, analytical data were transformed into ranks prior to ANOVA. The first ANOVA was performed using all the data treatments--swale stormwater, unsaturated-zone percolate, and shallow ground water with three additional ANOVA tests which examined each treatment (swale, percolate, and ground water) individually. Results of these ANOVA tests are given in table 9.

ANOVA results combining all of the data for swale stormwater, percolate, and ground water inferred that only the concentrations of iron, manganese, zinc, and hardness as  $\text{CaCO}_3$  were significantly different with depth, and only phosphorus and hardness were significantly different between the two sites. The inferred differences in depth (vertical distribution) of iron, manganese, and zinc concentrations generally resulted from an occasional greater concentration in either the swale or the near-surface unsaturated zone. At the Dixie plant, the greater concentrations tended to occur in the near-surface unsaturated zone, whereas at Pembroke Road, they usually occurred in the swale stormwater. The average zinc concentrations in the swale, for example, were about 20  $\mu\text{g/L}$  at Dixie plant and 65  $\mu\text{g/L}$  at Pembroke Road, about 300  $\mu\text{g/L}$  (0.5 foot, Dixie plant) and 70  $\mu\text{g/L}$  (0.5 foot, Pembroke Road) decreasing, respectively, to about 10 and 8  $\mu\text{g/L}$  in the shallow ground water. Similarly, average concentrations of iron were about 170  $\mu\text{g/L}$  at 0.5 foot decreasing to about 75  $\mu\text{g/L}$  in ground water at Dixie plant, but the greatest average concentration, about 70  $\mu\text{g/L}$ , occurred in the swale, decreasing to about 30  $\mu\text{g/L}$  in ground water at Pembroke Road.

Table 9.--Analysis of variance on ranks in water samples at the two test sites

[P-level, the probability that observed differences are due to chance rather than to the tested effect]

Dissolved constituent	Swale stormwater, unsaturated-zone percolate, and ground water		Swale stormwater	Ground water	Unsaturated-zone percolate	
	<u>Effects</u>		<u>Effects</u>	<u>Effects</u>	<u>Effects</u>	
	Site	Depth	Site	Site	Site	Depth
Chromium	0.821	0.531	0.446	0.945	0.752	0.466
Iron	.820	<sup>1</sup> .0001	.148	<sup>1</sup> .031	.307	<sup>1</sup> .042
Manganese	.199	<sup>1</sup> .0001	.458	.950	.075	<sup>1</sup> .006
Nickel	.744	.081	.485	.438	.087	.996
Zinc	.768	<sup>1</sup> .032	1.000	.256	<sup>1</sup> .063	<sup>1</sup> .039
Nitrogen	<sup>1</sup> .084	.238	.229	<sup>1</sup> .415	<sup>1</sup> .030	.450
Phosphorus	<sup>1</sup> .048	<sup>1</sup> .316	<sup>1</sup> .838	<sup>1</sup> .003	<sup>1</sup> .017	<sup>1</sup> .543
Hardness, as $\text{CaCO}_3$	<sup>1</sup> .003	<sup>1</sup> .0001	.018	.206	<sup>1</sup> .0001	<sup>1</sup> .022

<sup>1</sup>Effects significant at the 0.05 probability level.

Concentrations of water hardness at the two test sites were both significantly different with depth and between sites (table 9). The general distribution was: Dixie plant 49 mg/L (swale), 208 mg/L (2 feet), and 150 mg/L (ground water); Pembroke Road 31 mg/L (swale), 136 mg/L (2 feet), and 165 mg/L (ground water). The significant differences between the hardness concentrations in the unsaturated zone and in the ground-water samples suggest a very dominant regional mixing.

ANOVA tests, using just results of swale stormwater analyses, indicated that only hardness as  $\text{CaCO}_3$  was significantly different between sites (table 9). The average concentrations were 49 mg/L (Dixie plant) and 31 mg/L (Pembroke Road). ANOVA tests of just ground-water data indicated both iron and phosphorus concentrations were significantly different between the two test sites. Average concentrations of iron and phosphorus at Dixie plant and Pembroke Road were 75 and 31  $\mu\text{g/L}$  and 0.03 and 0.02 mg/L, respectively.

ANOVA tests of data from the unsaturated-zone lysimeters indicated several constituents were significantly different both with depths and sites. Particularly at Dixie plant, concentrations of iron, manganese, and zinc were notably greater in the upper-zone samples, whereas concentrations of hardness were greater in the lower zone. Nitrogen, phosphorus, and hardness in the unsaturated zone were significantly different between sites, all of which were in greater concentrations at Dixie plant. The average concentrations at Dixie plant and Pembroke Road, respectively, were 0.84 and 0.40 mg/L (nitrogen), 0.04 and 0.03 mg/L (phosphorus), and 200 and 117 mg/L (hardness as  $\text{CaCO}_3$ ).

The iron, zinc, nitrogen, and phosphorus data collected during this study and the Dade County study (Waller and others, 1984) were examined by ANOVA. For this general comparison, ranked data for swale stormwater, unsaturated-zone percolate, and ground water were pooled. Results inferred that both iron and zinc were significantly different at the 0.05 probability level among the two Broward County and Dade County test sites, with overall concentrations greater at the Dade County test site. Nitrogen and phosphorus were also significantly different with the greater concentrations at the Dade County test site. Nitrogen averaged about 1 mg/L at the Broward County test sites and 8.4 mg/L at the Dade County site, and phosphorus about 0.05 and 0.37 mg/L, respectively. The greater concentrations of nitrogen and phosphorus at the Dade County site may have been partly due to fertilizer application.

#### SUMMARY

Results of this study suggest that stormwater runoff from highway surfaces is a contributing factor in the accumulation of selected constituents in near-surface lithologic material. Analyses of lithologic material in highway swales that have been in contact with percolating stormwater at two test sites in Broward County indicated concentrations of lead ranging from 1,000 to 6,600  $\mu\text{g/kg}$ , iron from 490 to 2,400  $\mu\text{g/kg}$ , and zinc from 90 to 1,800  $\mu\text{g/kg}$  between 0 and 0.5 foot below land surface. Concentrations of this magnitude were not detected in lithologic samples collected at an unaffected control site. Results of nonparametric ANOVA inferred significant differences in concentrations of most constituents in the lithologic material with depth, but inferred differences for these same constituents were not as notable among the sites. The absence of a significant effect among the sites was largely because of the relatively homogeneous distribution of concentrations in lithologic material below 0.5 to 1.0 foot. Overall, the greater concentrations for most constituents usually occurred at

the Pembroke Road test site. However, concentrations of phosphorus and ammonia nitrogen were notably greater at the control site, and ANOVA indicated both were significantly different among the sites.

For five selected constituents, iron, lead, zinc, nitrogen, and phosphorus, an ANOVA inferred that concentrations of iron, kjeldahl nitrogen, and phosphorus in lithologic material were significantly different among the two Broward County test sites and that in Dade County as reported by Waller and others in 1984. The inferred statistical differences were attributed to the generally greater concentrations throughout the lithologic vertical at the Dade County test site.

Analyses of samples of swale stormwater prior to percolation, of unsaturated-zone percolate, and the shallow ground water, collected at the two test sites during 12 storms from May through November 1983, indicated generally low, but extremely variable concentrations. Results of nonparametric ANOVA, however, inferred such dissolved constituents as iron, manganese, zinc, and hardness as  $\text{CaCO}_3$  varied significantly among the swale, the unsaturated zone, and the shallow ground water at the Dixie plant and Pembroke Road test sites. ANOVA tests of individual treatments (swale, unsaturated-zone percolate, and ground water) inferred some differences between the two sites, with most significant differences between the two test sites occurring in constituents within the unsaturated-zone percolates. Only concentrations of iron and phosphorus in ground water and hardness as  $\text{CaCO}_3$  in swale stormwater were inferred to be significantly different between the test sites.

Infrequently, undesirable concentrations of some constituents were detected in the swale stormwater and near-surface percolate during the sampling period. However, neither the lithologic nor stormwater analyses indicated an obvious impact on local ground water caused by highway runoff. The companion study of the impacts of highway runoff in unsaturated limestone in Dade County, Waller and others, in 1984, also reported that there was little evidence of undesirable constituents reaching the water table.

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## **SUPPLEMENTARY DATA**

Chemical analysis of highway runoff at varying depth intervals from  
storm 1, May 26, 1983, at Dixie water-treatment plant

[Constituents shown in capital letters are the most common highway contaminants. There was no sample in the lysimeter for the 6.0-foot depth.  $\mu\text{g/L}$  = microgram per liter;  $\mu\text{S/cm}$  = microSiemens per centimeter;  $\text{mg/L}$  = milligram per liter;  $<$  = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface						Water table
	Swale	0.5	1.0	2.0	3.0	6.0	
Barium, $\mu\text{g/L}$	34	80	99	61	110	--	29
Beryllium, $\mu\text{g/L}$	<.5	<.5	<.5	<.5	<.5	--	<.5
Cadmium, $\mu\text{g/L}$	<1	<1	<1	<1	<1	--	<1
CHROMIUM, $\mu\text{g/L}$	1	--	3	9	8	--	3
Cobalt, $\mu\text{g/L}$	<3	<3	<3	<3	<3	--	<3
COPPER, $\mu\text{g/L}$	10	10	10	<10	10	--	<10
IRON, $\mu\text{g/L}$	7	12	11	5	29	--	92
LEAD, $\mu\text{g/L}$	<10	30	20	20	10	--	<10
Lithium, $\mu\text{g/L}$	4	41	28	8	<4	--	<4
Manganese, $\mu\text{g/L}$	3	1	2	<1	6	--	3
MERCURY, $\mu\text{g/L}$	<.1	<.1	<.1	<.1	<.1	--	<.1
Molybdenum, $\mu\text{g/L}$	<10	30	<10	<10	<10	--	<10
NICKEL, $\mu\text{g/L}$	4	--	4	5	1	--	3
Strontium, $\mu\text{g/L}$	140	670	970	1,100	640	--	460
Vanadium, $\mu\text{g/L}$	7	230	29	14	70	--	6
ZINC, $\mu\text{g/L}$	8	43	32	36	76	--	4
Calcium, $\text{mg/L}$	21	64	93	83	66	--	48
Magnesium, $\text{mg/L}$	.66	1.3	2.5	1.8	1.7	--	.96
Hardness, $\text{mg/L}$	55	170	240	220	170	--	120
Sodium, $\text{mg/L}$	2.7	32	25	22	15	--	2.8
Silica, $\text{mg/L}$	1	58	34	29	20	--	2.3
Specific conductance, $\mu\text{S/cm}$ at 25 °C	119	--	570	480	480	--	250
TOTAL NITROGEN as N, $\text{mg/L}$	3.2	--	--	3.35	2.04	--	.27
ORGANIC NITROGEN as N, $\text{mg/L}$	2.2	--	--	.92	.3	--	.19
AMMONIA NITROGEN as N, $\text{mg/L}$	.3	--	--	.02	.02	--	.02
NITRITE as N, $\text{mg/L}$	.05	--	--	.01	.02	--	.02
NITRATE as N, $\text{mg/L}$	.65	--	--	2.4	1.7	--	.04
Total phosphorus as P, $\text{mg/L}$	.28	--	--	.06	.06	--	.05
ORTHOPHOSPHORUS as P, $\text{mg/L}$	.15	--	--	.05	.05	--	.04



Chemical analysis of highway runoff at varying depth intervals from  
storm 1, May 26, 1983, at Pembroke Road

[Constituents shown in capital letters are the most common highway contaminants. There were no samples in the lysimeter for the 0.5-, 2.0-, and 6.0-foot depth.  $\mu\text{g/L}$  = microgram per liter;  $\mu\text{S/cm}$  = microSiemens per centimeter;  $\text{mg/L}$  = milligram per liter;  $<$  = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface					Water table
	Swale	0.5	1.0	2.0	6.0	
Barium, $\mu\text{g/L}$	72	--	72	--	--	31
Beryllium, $\mu\text{g/L}$	<.5	--	<.5	--	--	<.5
Cadmium, $\mu\text{g/L}$	2	--	<1	--	--	<1
CHROMIUM, $\mu\text{g/L}$	2	--	--	--	--	12
Cobalt, $\mu\text{g/L}$	<3	--	<3	--	--	<3
COPPER, $\mu\text{g/L}$	40	--	20	--	--	<10
IRON, $\mu\text{g/L}$	160	--	19	--	--	64
LEAD, $\mu\text{g/L}$	<10	--	10	--	--	<10
Lithium, $\mu\text{g/L}$	<4	--	12	--	--	<4
Manganese, $\mu\text{g/L}$	40	--	2	--	--	5
MERCURY, $\mu\text{g/L}$	.4	--	.1	--	--	<.1
Molybdenum, $\mu\text{g/L}$	<10	--	<10	--	--	<10
NICKEL, $\mu\text{g/L}$	12	--	--	--	--	2
Strontium, $\mu\text{g/L}$	180	--	390	--	--	470
Vanadium, $\mu\text{g/L}$	7	--	25	--	--	<6
ZINC, $\mu\text{g/L}$	400	--	19	--	--	4
Calcium, $\text{mg/L}$	40	--	53	--	--	70
Magnesium, $\text{mg/L}$	1.5	--	1.8	--	--	1.2
Hardness, $\text{mg/L}$	--	--	140	--	--	180
Sodium, $\text{mg/L}$	8.6	--	10	--	--	4.3
Silica, $\text{mg/L}$	1.2	--	13	--	--	1.6
Specific conductance, $\mu\text{S/cm}$ at 25 °C	240	--	--	--	--	355
TOTAL NITROGEN as N, $\text{mg/L}$	6.92	--	--	--	--	.47
ORGANIC NITROGEN as N $\text{mg/L}$	4.8	--	--	--	--	.24
AMMONIA NITROGEN as N $\text{mg/L}$	.32	--	--	--	--	.04
NITRITE as N, $\text{mg/L}$	.1	--	--	--	--	.01
NITRATE as N, $\text{mg/L}$	1.7	--	--	--	--	.18
Total phosphorus as P $\text{mg/L}$	.56	--	--	--	--	.03
ORTHOPHOSPHORUS as P, $\text{mg/L}$	.18	--	--	--	--	.02

Chemical analysis of highway runoff at varying depth intervals from storm 2,  
June 1, 1983, at Dixie water-treatment plant

[Constituents shown in capital letters are the most common highway contaminants.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter;  $\mu\text{S/cm}$  = microSiemens per centimeter; Pt-Co = platinum-cobalt; < = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface						Water table
	Swale	0.5	1.0	2.0	3.0	6.0	
Barium, $\mu\text{g/L}$	78	110	84	77	82	89	42
Beryllium, $\mu\text{g/L}$	<.5	<.5	<.5	<.5	<.5	<.5	<.5
Cadmium, $\mu\text{g/L}$	<1	1	<1	<1	<1	<1	<1
CHROMIUM, $\mu\text{g/L}$	2	--	2	12	9	<10	2
Cobalt, $\mu\text{g/L}$	<3	<3	<3	<3	<3	<3	<3
COPPER, $\mu\text{g/L}$	10	30	10	<10	10	<10	<10
IRON, $\mu\text{g/L}$	60	330	8	6	6	8	100
LEAD, $\mu\text{g/L}$	<10	10	<10	20	10	20	<10
Lithium, $\mu\text{g/L}$	<4	<4	<4	<4	<4	13	<4
Manganese, $\mu\text{g/L}$	6	49	1	1	<1	1	4
MERCURY, $\mu\text{g/L}$	<.1	.1	.2	<.1	.2	.1	.1
Molybdenum, $\mu\text{g/L}$	<10	<10	<10	<10	<10	<10	<10
NICKEL, $\mu\text{g/L}$	5	--	2	6	6	4	1
Strontium, $\mu\text{g/L}$	200	250	720	1,000	960	1,100	480
Vanadium, $\mu\text{g/L}$	<6	13	14	12	6	21	10
ZINC, $\mu\text{g/L}$	9	560	<3	9	<3	<3	14
Calcium, $\text{mg/L}$	28	53	72	84	82	100	50
Magnesium, $\text{mg/L}$	.52	2.1	2	2.2	2.2	2.6	1
Hardness, $\text{mg/L}$	72	140	190	220	220	260	130
Sodium, $\text{mg/L}$	1.7	12	6.8	15	11	24	4.5
Silica, $\text{mg/L}$	2.8	1.4	12	11	10	27	2.2
Specific conductance, $\mu\text{S/cm}$ at 25 °C	140	--	--	--	--	--	250
Bicarbonate, $\text{mg/L}$	92	--	--	--	--	--	139
Chloride, $\text{mg/L}$	2.5	--	--	--	--	--	9.6
Fluoride, $\text{mg/L}$	.1	--	--	--	--	--	.2
Potassium, $\text{mg/L}$	.4	--	--	--	--	--	.5
Sulfate, $\text{mg/L}$	5.7	--	--	--	--	--	17
Dissolved solids, $\text{mg/L}$	9.8	--	--	--	--	--	219
pH, units	7	--	--	--	--	--	7.5
Color, Pt-Co units	20	--	--	--	--	--	60
TOTAL NITROGEN as N, $\text{mg/L}$	1.1	--	--	--	--	--	.37
ORGANIC NITROGEN as N, $\text{mg/L}$	1	--	--	--	--	--	.3
AMMONIA NITROGEN as N, $\text{mg/L}$	.08	--	--	--	--	--	.02
NITRITE as N, $\text{mg/L}$	.01	--	--	--	--	--	.01
NITRATE as N, $\text{mg/L}$	<.01	--	--	--	--	--	.04
Total phosphorus as P, $\text{mg/L}$	.1	--	--	--	--	--	.03
ORTHOPHOSPHORUS as P, $\text{mg/L}$	.04	--	--	--	--	--	.03

Chemical analysis of highway runoff at varying depth intervals from storm 2,  
June 1, 1983, at Pembroke Road

[Constituents shown in capital letters are the most common highway  
contaminants.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter;  
 $\mu\text{S/cm}$  = microSiemens per centimeter;  $<$  = concentration below analytical  
detection limit; and -- = no data]

Constituent	Depth, feet below land surface					Water table
	Swale	0.5	1.0	2.0	6.0	
Barium, $\mu\text{g/L}$	39	150	52	51	58	41
Beryllium, $\mu\text{g/L}$	<.5	<.5	<.5	<.5	<.5	<.5
Cadmium, $\mu\text{g/L}$	<1	<1	<1	<1	<1	1
CHROMIUM, $\mu\text{g/L}$	--	--	2	11	3	9
Cobalt, $\mu\text{g/L}$	<3	<3	<3	<3	<3	<3
COPPER, $\mu\text{g/L}$	<10	<10	<10	<10	<10	<10
IRON, $\mu\text{g/L}$	61	15	13	5	6	23
LEAD, $\mu\text{g/L}$	<10	<10	<10	<10	<10	<10
Lithium, $\mu\text{g/L}$	<4	<4	5	<4	9	<4
Manganese, $\mu\text{g/L}$	4	<1	1	<1	<1	2
MERCURY, $\mu\text{g/L}$	--	--	.1	<.1	<.1	<.1
Molybdenum, $\mu\text{g/L}$	<10	<10	<10	<10	<10	<10
NICKEL, $\mu\text{g/L}$	--	--	6	4	2	5
Strontium, $\mu\text{g/L}$	55	460	420	480	480	480
Vanadium, $\mu\text{g/L}$	<6	18	21	10	49	9
ZINC, $\mu\text{g/L}$	<3	12	<3	<3	<3	11
Calcium, $\text{mg/L}$	8.5	60	55	57	56	66
Magnesium, $\text{mg/L}$	.28	1.5	1.5	.73	.69	.93
Hardness, $\text{mg/L}$	22	160	140	150	140	170
Sodium, $\text{mg/L}$	1.8	3	5.6	3.3	3	7.5
Silica, $\text{mg/L}$	.22	12	17	15	36	1.6
Specific conductance, $\mu\text{S/cm}$ at 25 °C	114	--	--	--	--	345
TOTAL NITROGEN as N, $\text{mg/L}$	1.5	--	--	--	--	1.02
ORGANIC NITROGEN as N, $\text{mg/L}$	.63	--	--	--	--	.4
AMMONIA NITROGEN as N, $\text{mg/L}$	.42	--	--	--	--	.01
NITRITE as N, $\text{mg/L}$	.02	--	--	--	--	.01
NITRATE as N, $\text{mg/L}$	.43	--	--	--	--	.6
Total phosphorus as P, $\text{mg/L}$	.11	--	--	--	--	.02
ORTHOPHOSPHORUS as P, $\text{mg/L}$	.05	--	--	--	--	.01

Chemical analysis of highway runoff at varying depth intervals from storm 3,  
June 8, 1983, at Dixie water-treatment plant

[Constituents shown in capital letters are the most common highway contaminants. There was no sample in the lysimeter at the 6.0-foot depth. The water table was under water, unable to sample. mg/L = milligram per liter; < = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface						Water table
	Swale	0.5	1.0	2.0	3.0	6.0	
Chloride, mg/L	3.2	--	3	5	5	--	--
Fluoride, mg/L	.1	--	.2	.2	.3	--	--
Sulfate, mg/L	5.9	--	2.3	12	16	--	--
Dissolved solids, mg/L	63	--	204	258	280	--	--
TOTAL NITROGEN as N, mg/L	.73	1.07	.48	.58	.7	--	--
ORGANIC NITROGEN as N, mg/L	.42	.95	.37	.17	.57	--	--
AMMONIA NITROGEN as N, mg/L	.06	.04	.02	.03	.03	--	--
NITRITE as N, mg/L	.04	.01	<.01	<.01	<.01	--	--
NITRATE as N, mg/L	.21	.07	.08	.37	.09	--	--
Total phosphorus as P, mg/L	.07	.08	.05	.03	.07	--	--
ORTHOPHOSPHORUS as P, mg/L	.03	.06	.02	.02	.04	--	--

Chemical analysis of highway runoff at varying depth intervals from storm 3,  
June 8, 1983, at Pembroke Road

[Constituents shown in capital letters are the most common highway contaminants. Lysimeter damaged at the 6.0-foot depth. Water table underwater, unable to sample. mg/L = milligram per liter; < = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface					Water table
	Swale	0.5	1.0	2.0	6.0	
Chloride, mg/L	6.6	--	3.2	7	--	--
Fluoride, mg/L	.1	--	.2	.2	--	--
Sulfate, mg/L	1	--	5.2	7.8	--	--
Dissolved solids, mg/L	76	--	132	204	--	--
TOTAL NITROGEN as N, mg/L	.88	0.43	.66	.42	--	--
ORGANIC NITROGEN as N, mg/L	.6	.29	.51	.36	--	--
AMMONIA NITROGEN as N, mg/L	.03	.01	.03	.01	--	--
NITRITE as N, mg/L	.06	<.01	.01	<.01	--	--
NITRATE as N, mg/L	.19	.13	.11	.04	--	--
Total phosphorus as P, mg/L	.05	.02	.04	.02	--	--
ORTHOPHOSPHORUS as P, mg/L	.02	.01	.03	.01	--	--

Chemical analysis of highway runoff at varying depth intervals  
from storm 4, June 9, 1983, at Dixie water-treatment plant

[Constituents shown in capital letters are the most common highway contaminants. No sample was collected at the swale. Sample volumes at the 0.5- and 1.0-foot depth were too small to analyze for all constituents. There was no sample in the lysimeter at the 6.0-foot depth.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter;  $<$  = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface						Water table
	Swale	0.5	1.0	2.0	3.0	6.0	
Barium, $\mu\text{g/L}$	--	--	--	73	88	--	40
Beryllium, $\mu\text{g/L}$	--	--	--	<.5	<.5	--	<.5
Cadmium, $\mu\text{g/L}$	--	--	--	<1	<1	--	<1
CHROMIUM, $\mu\text{g/L}$	--	--	2	9	18	--	9
Cobalt, $\mu\text{g/L}$	--	--	--	<3	<3	--	<3
COPPER, $\mu\text{g/L}$	--	--	--	<10	<10	--	<10
IRON, $\mu\text{g/L}$	--	--	--	8	8	--	30
LEAD, $\mu\text{g/L}$	--	--	--	<10	<10	--	<10
Lithium, $\mu\text{g/L}$	--	--	--	<4	<4	--	<4
Manganese, $\mu\text{g/L}$	--	--	--	<1	<1	--	2
MERCURY, $\mu\text{g/L}$	--	0.7	.7	<.1	.1	--	<.1
Molybdenum, $\mu\text{g/L}$	--	--	--	<10	<10	--	<10
NICKEL, $\mu\text{g/L}$	--	3	4	8	4	--	2
Strontium, $\mu\text{g/L}$	--	--	--	880	930	--	520
Vanadium, $\mu\text{g/L}$	--	--	--	7	<6	--	21
ZINC, $\mu\text{g/L}$	--	--	--	13	10	--	17
Calcium, $\text{mg/L}$	--	--	--	75	80	--	53
Magnesium, $\text{mg/L}$	--	--	--	1.8	1.8	--	1.1
Hardness, $\text{mg/L}$	--	--	--	200	210	--	140
Sodium, $\text{mg/L}$	--	--	--	6.7	7.3	--	4.5
Silica, $\text{mg/L}$	--	--	--	8.3	8.5	--	2.5

Chemical analysis of highway runoff at varying depth intervals from storm 4,  
June 9, 1983, at Pembroke Road

[Constituents shown in capital letters are the most common highway contaminants. No sample was collected at the swale. Sample volume at the 1.0-foot depth was too small to analyze for all constituents. Lysimeter destroyed at the 6.0-foot depth.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter;  $<$  = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface					Water table
	Swale	0.5	1.0	2.0	6.0	
Barium, $\mu\text{g/L}$	--	100	--	50	--	44
Beryllium, $\mu\text{g/L}$	--	<.5	--	<.5	--	<.5
Cadmium, $\mu\text{g/L}$	--	<1	--	<1	--	<1
CHROMIUM, $\mu\text{g/L}$	--	60	3	10	--	8
Cobalt, $\mu\text{g/L}$	--	<3	--	<3	--	<3
COPPER, $\mu\text{g/L}$	--	<10	--	<10	--	<10
IRON, $\mu\text{g/L}$	--	10	--	4	--	14
LEAD, $\mu\text{g/L}$	--	<10	--	<10	--	<10
Lithium, $\mu\text{g/L}$	--	<4	--	<4	--	<4
Manganese, $\mu\text{g/L}$	--	<1	--	<1	--	1
MERCURY, $\mu\text{g/L}$	--	.2	.5	<.1	--	<.1
Molybdenum, $\mu\text{g/L}$	--	<10	--	<10	--	<10
NICKEL, $\mu\text{g/L}$	--	--	1	3	--	3
Strontium, $\mu\text{g/L}$	--	240	--	450	--	440
Vanadium, $\mu\text{g/L}$	--	10	--	<6	--	8
ZINC, $\mu\text{g/L}$	--	<3	--	<3	--	<3
Calcium, $\text{mg/L}$	--	32	--	56	--	58
Magnesium, $\text{mg/L}$	--	.64	--	.67	--	.77
Hardness, $\text{mg/L}$	--	83	--	140	--	150
Sodium, $\text{mg/L}$	--	1.9	--	2.3	--	4
Silica, $\text{mg/L}$	--	7.4	--	9.5	--	1.5

Chemical analysis of highway runoff at varying depth intervals from storm 5,  
July 27, 1983, at Dixie water-treatment plant

[Constituents shown in capital letters are the most common highway contaminants. The lysimeter was destroyed at the 0.5- and 6.0-foot depths. There was no sample in the lysimeter at the 3.0-foot depth. Rainfall did not reach the water table.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter;  $<$  = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface						Water table
	Swale	0.5	1.0	2.0	3.0	6.0	
Barium, $\mu\text{g/L}$	45	--	200	150	--	--	--
Beryllium, $\mu\text{g/L}$	<.5	--	<.5	<.5	--	--	--
Cadmium, $\mu\text{g/L}$	<1	--	<1	<1	--	--	--
CHROMIUM, $\mu\text{g/L}$	8	--	--	10	--	--	--
Cobalt, $\mu\text{g/L}$	<3	--	<3	<3	--	--	--
COPPER, $\mu\text{g/L}$	<10	--	40	<10	--	--	--
IRON, $\mu\text{g/L}$	39	--	29	16	--	--	--
LEAD, $\mu\text{g/L}$	<10	--	20	20	--	--	--
Lithium, $\mu\text{g/L}$	<4	--	5	16	--	--	--
Manganese, $\mu\text{g/L}$	<1	--	1	<1	--	--	--
MERCURY, $\mu\text{g/L}$	<.1	--	.4	<.1	--	--	--
Molybdenum, $\mu\text{g/L}$	<10	--	<10	<10	--	--	--
NICKEL, $\mu\text{g/L}$	1	--	--	--	--	--	--
Strontium, $\mu\text{g/L}$	69	--	670	1,500	--	--	--
Vanadium, $\mu\text{g/L}$	14	--	17	14	--	--	--
ZINC, $\mu\text{g/L}$	4	--	55	15	--	--	--
Calcium, $\text{mg/L}$	11	--	69	130	--	--	--
Magnesium, $\text{mg/L}$	.33	--	2.4	2.8	--	--	--
Hardness, $\text{mg/L}$	29	--	180	340	--	--	--
Sodium, $\text{mg/L}$	1.4	--	15	24	--	--	--
Silica, $\text{mg/L}$	.59	--	13	17	--	--	--



Chemical analysis of highway runoff at varying depth intervals from storm 5,  
July 27, 1983, at Pembroke Road

[Constituents shown in capital letters are the most common highway contaminants. No samples in lysimeter at the 0.5-, 1.0-, and 6.0-foot depths.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter; < = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface					Water table
	Swale	0.5	1.0	2.0	6.0	
Barium, $\mu\text{g/L}$	49	--	--	59	--	28
Beryllium, $\mu\text{g/L}$	<.5	--	--	<.5	--	<.5
Cadmium, $\mu\text{g/L}$	<1	--	--	<1	--	<1
CHROMIUM, $\mu\text{g/L}$	2	--	--	2	--	1
Cobalt, $\mu\text{g/L}$	<3	--	--	<3	--	<3
COPPER, $\mu\text{g/L}$	<10	--	--	10	--	<10
IRON, $\mu\text{g/L}$	5	--	--	21	--	5
LEAD, $\mu\text{g/L}$	<10	--	--	<10	--	<10
Lithium, $\mu\text{g/L}$	<4	--	--	<4	--	<4
Manganese, $\mu\text{g/L}$	2	--	--	2	--	2
MERCURY, $\mu\text{g/L}$	.4	--	--	.1	--	<.1
Molybdenum, $\mu\text{g/L}$	<10	--	--	<10	--	<10
NICKEL, $\mu\text{g/L}$	13	--	--	--	--	1
Strontium, $\mu\text{g/L}$	530	--	--	260	--	520
Vanadium, $\mu\text{g/L}$	<6	--	--	12	--	<6
ZINC, $\mu\text{g/L}$	<3	--	--	13	--	5
Calcium, $\text{mg/L}$	68	--	--	33	--	68
Magnesium, $\text{mg/L}$	.82	--	--	.32	--	.85
Hardness, $\text{mg/L}$	--	--	--	84	--	170
Sodium, $\text{mg/L}$	3	--	--	2.9	--	2.9
Silica, $\text{mg/L}$	1.6	--	--	7.9	--	1.6

Chemical analysis of highway runoff at varying depth intervals from storm 6,  
July 28, 1983, at Dixie water-treatment plant

[Constituents shown in capital letters are the most common highway contaminants. The lysimeter was destroyed at the 0.5- and 6.0-foot depths.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter;  $\mu\text{S/cm}$  = microSiemens per centimeter;  $<$  = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface						Water table
	Swale	0.5	1.0	2.0	3.0	6.0	
Barium, $\mu\text{g/L}$	50	--	95	73	110	--	23
Beryllium, $\mu\text{g/L}$	<.5	--	<.5	<.5	<.5	--	<.5
Cadmium, $\mu\text{g/L}$	<1	--	<1	<1	<1	--	<1
CHROMIUM, $\mu\text{g/L}$	3	--	10	1	2	--	9
Cobalt, $\mu\text{g/L}$	<3	--	<3	<3	<3	--	<3
COPPER, $\mu\text{g/L}$	20	--	20	10	10	--	<10
IRON, $\mu\text{g/L}$	35	--	16	10	10	--	12
LEAD, $\mu\text{g/L}$	<10	--	10	10	20	--	<10
Lithium, $\mu\text{g/L}$	<4	--	21	<4	7	--	<4
Manganese, $\mu\text{g/L}$	11	--	1	<1	<1	--	<1
MERCURY, $\mu\text{g/L}$	<.1	--	.1	<.1	.2	--	<.1
Molybdenum, $\mu\text{g/L}$	<10	--	<10	<10	<10	--	<10
NICKEL, $\mu\text{g/L}$	3	--	5	3	5	--	2
Strontium, $\mu\text{g/L}$	130	--	630	750	1,100	--	560
Vanadium, $\mu\text{g/L}$	11	--	15	9	<6	--	39
ZINC, $\mu\text{g/L}$	48	--	26	29	11	--	22
Calcium, $\text{mg/L}$	20	--	67	71	93	--	58
Magnesium, $\text{mg/L}$	.55	--	2.2	1.7	2	--	1.1
Hardness, $\text{mg/L}$	52	--	180	190	240	--	150
Sodium, $\text{mg/L}$	4.1	--	11	11	15	--	3.5
Silica, $\text{mg/L}$	.83	--	14	11	9.5	--	2.9
Specific conductance, $\mu\text{S/cm}$ at 25 °C	195	--	--	--	--	--	295

Chemical analysis of highway runoff at varying depth intervals from  
storm 6, July 28, 1983, at Pembroke Road

[Constituents shown in capital letters are the most common highway contaminants. No sample in lysimeter at the 6.0-foot depth.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter;  $\mu\text{S/cm}$  = microSiemens per centimeter;  $<$  = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface					Water table
	Swale	0.5	1.0	2.0	6.0	
Barium, $\mu\text{g/L}$	39	120	54	55	--	35
Beryllium, $\mu\text{g/L}$	<.5	<.5	<.5	<.5	--	<.5
Cadmium, $\mu\text{g/L}$	<1	<1	<1	<1	--	<1
CHROMIUM, $\mu\text{g/L}$	3	<10	2	10	--	2
Cobalt, $\mu\text{g/L}$	<3	<3	<3	<3	--	<3
COPPER, $\mu\text{g/L}$	<10	10	10	<10	--	<10
IRON, $\mu\text{g/L}$	66	43	13	7	--	5
LEAD, $\mu\text{g/L}$	<10	<10	<10	<10	--	<10
Lithium, $\mu\text{g/L}$	<4	8	9	<4	--	<4
Manganese, $\mu\text{g/L}$	4	7	<1	<1	--	<1
MERCURY, $\mu\text{g/L}$	<.1	.5	<.1	<.1	--	<.1
Molybdenum, $\mu\text{g/L}$	<10	<10	<10	<10	--	<10
NICKEL, $\mu\text{g/L}$	1	--	3	2	--	1
Strontium, $\mu\text{g/L}$	50	260	210	400	--	560
Vanadium, $\mu\text{g/L}$	<6	14	12	7	--	<6
ZINC, $\mu\text{g/L}$	17	150	14	13	--	<3
Calcium, $\text{mg/L}$	11	43	30	49	--	73
Magnesium, $\text{mg/L}$	.28	.81	.94	.34	--	.91
Hardness, $\text{mg/L}$	29	110	79	120	--	190
Sodium, $\text{mg/L}$	1.1	2.9	2.8	2.4	--	3.6
Silica, $\text{mg/L}$	.28	11	10	9.3	--	1.7
Specific conductance, $\mu\text{S/cm}$ at 25 °C	115	--	--	--	--	355

Chemical analysis of highway runoff at varying depth intervals from storm 7,  
August 23, 1983, at Dixie water-treatment plant

[Constituents shown in capital letters are the most common highway contaminants. Lysimeter destroyed at the 0.5- and 6.0-foot depths.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter;  $<$  = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface						Water table
	Swale	0.5	1.0	2.0	3.0	6.0	
Barium, $\mu\text{g/L}$	34	--	62	62	160	--	29
Beryllium, $\mu\text{g/L}$	<.5	--	<.5	<.5	<.5	--	<.5
Cadmium, $\mu\text{g/L}$	<1	--	<1	<1	<1	--	<1
CHROMIUM, $\mu\text{g/L}$	6	--	--	--	--	--	--
Cobalt, $\mu\text{g/L}$	<3	--	<3	<3	<3	--	<3
COPPER, $\mu\text{g/L}$	10	--	30	10	10	--	<10
IRON, $\mu\text{g/L}$	46	--	1,300	8	18	--	140
LEAD, $\mu\text{g/L}$	<10	--	<10	<10	<10	--	<10
Lithium, $\mu\text{g/L}$	<4	--	5	8	6	--	16
Manganese, $\mu\text{g/L}$	5	--	15	<1	<1	--	<1
MERCURY, $\mu\text{g/L}$	<.1	--	<.1	<.1	.4	--	.1
Molybdenum, $\mu\text{g/L}$	<10	--	<10	<10	<10	--	<10
NICKEL, $\mu\text{g/L}$	2	--	5	2	--	--	2
Strontium, $\mu\text{g/L}$	91	--	510	720	800	--	640
Vanadium, $\mu\text{g/L}$	<6	--	7	<6	<6	--	24
ZINC, $\mu\text{g/L}$	25	--	76	11	6	--	9
Calcium, $\text{mg/L}$	14	--	60	74	77	--	67
Magnesium, $\text{mg/L}$	.28	--	1.7	1.7	1.4	--	1.2
Hardness, $\text{mg/L}$	36	--	160	190	200	--	170
Sodium, $\text{mg/L}$	1.8	--	2.4	2.6	3	--	4.8
Silica, $\text{mg/L}$	.71	--	11	12	13	--	3
TOTAL NITROGEN as N, $\text{mg/L}$	.51	--	--	--	--	--	.66
ORGANIC NITROGEN as N, $\text{mg/L}$	.23	--	--	--	--	--	.19
AMMONIA NITROGEN as N, $\text{mg/L}$	.02	--	--	--	--	--	.02
NITRITE as N, $\text{mg/L}$	.02	--	--	--	--	--	.04
NITRATE as N, $\text{mg/L}$	.24	--	--	--	--	--	.41
Total phosphorus as P, $\text{mg/L}$	.1	--	--	--	--	--	.04
ORTHOPHOSPHORUS as P, $\text{mg/L}$	.08	--	--	--	--	--	.02

Chemical analysis of highway runoff at varying depth intervals from storm 7,  
August 23, 1983, at Pembroke Road

[Constituents shown in capital letters are the most common highway contaminants. Lysimeter damaged at the 0.5-foot depth.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligrams per liter;  $<$  = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface					Water table
	Swale	0.5	1.0	2.0	6.0	
Barium, $\mu\text{g/L}$	34	--	55	44	45	29
Beryllium, $\mu\text{g/L}$	<.5	--	<.5	<.5	<.5	<.5
Cadmium, $\mu\text{g/L}$	<1	--	<1	<1	<1	<1
CHROMIUM, $\mu\text{g/L}$	8	--	--	--	--	--
Cobalt, $\mu\text{g/L}$	<3	--	<3	<3	<3	<3
COPPER, $\mu\text{g/L}$	<10	--	<10	<10	<10	<10
IRON, $\mu\text{g/L}$	84	--	27	11	10	42
LEAD, $\mu\text{g/L}$	40	--	<10	<10	<10	<10
Lithium, $\mu\text{g/L}$	<4	--	<4	<4	5	<4
Manganese, $\mu\text{g/L}$	4	--	5	<1	<1	2
MERCURY, $\mu\text{g/L}$	<.1	--	<.1	<.1	<.1	<.1
Molybdenum, $\mu\text{g/L}$	<10	--	<10	<10	<10	<10
NICKEL, $\mu\text{g/L}$	1	--	3	2	2	2
Strontium, $\mu\text{g/L}$	45	--	150	320	410	440
Vanadium, $\mu\text{g/L}$	<6	--	<6	<6	14	<6
ZINC, $\mu\text{g/L}$	35	--	62	8	12	5
Calcium, $\text{mg/L}$	11	--	25	44	53	61
Magnesium, $\text{mg/L}$	.4	--	.37	.09	.64	.65
Hardness, $\text{mg/L}$	29	--	64	110	140	160
Sodium, $\text{mg/L}$	.9	--	1.5	1.1	1.6	2.3
Silica, $\text{mg/L}$	.25	--	7.7	8.9	25	1.6
TOTAL NITROGEN as N, $\text{mg/L}$	.5	--	.49	.61	.18	.73
ORGANIC NITROGEN as N, $\text{mg/L}$	.38	--	.34	.54	.12	.18
AMMONIA NITROGEN as N, $\text{mg/L}$	.02	--	.03	.02	.02	.01
NITRITE as N, $\text{mg/L}$	.01	--	<.01	<.01	<.01	<.01
NITRATE as N, $\text{mg/L}$	.09	--	.11	.04	.03	.53
Total phosphorus as P, $\text{mg/L}$	.08	--	.04	.07	.03	.03
ORTHOPHOSPHORUS as P, $\text{mg/L}$	.07	--	.02	.01	.02	.01

Chemical analysis of highway runoff at varying depth intervals from storm 8,  
September 1, 1983, at Dixie water-treatment plant

[Constituents shown in capital letters are the most common highway contaminants. Lysimeter destroyed at the 0.5- and 6.0-foot depths. Sample volume at the 1.0-foot depth too small to analyze for all constituents.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter;  $<$  = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface						Water table
	Swale	0.5	1.0	2.0	3.0	6.0	
Barium, $\mu\text{g/L}$	46	--	--	65	58	--	33
Beryllium, $\mu\text{g/L}$	<.5	--	--	<.5	<.5	--	<.5
Cadmium, $\mu\text{g/L}$	<1	--	--	<1	<1	--	<1
CHROMIUM, $\mu\text{g/L}$	<1	--	--	--	<1	--	<1
Cobalt, $\mu\text{g/L}$	<3	--	--	<3	<3	--	<3
COPPER, $\mu\text{g/L}$	<10	--	--	<10	<10	--	<10
IRON, $\mu\text{g/L}$	28	--	--	15	9	--	67
LEAD, $\mu\text{g/L}$	<10	--	--	<10	<10	--	<10
Lithium, $\mu\text{g/L}$	<4	--	--	5	5	--	<4
Manganese, $\mu\text{g/L}$	8	--	--	<1	<1	--	<1
MERCURY, $\mu\text{g/L}$	<.1	--	0.1	<.1	<.1	--	.1
Molybdenum, $\mu\text{g/L}$	<10	--	--	<10	<10	--	<10
NICKEL, $\mu\text{g/L}$	3	--	2	2	2	--	1
Strontium, $\mu\text{g/L}$	91	--	--	780	810	--	630
Vanadium, $\mu\text{g/L}$	<6	--	--	<6	<6	--	20
ZINC, $\mu\text{g/L}$	31	--	--	12	18	--	7
Calcium, $\text{mg/L}$	18	--	--	82	82	--	65
Magnesium, $\text{mg/L}$	.27	--	--	1.7	1.5	--	1.1
Hardness, $\text{mg/L}$	46	--	--	210	210	--	170
Sodium, $\text{mg/L}$	.9	--	--	1.8	1.9	--	5
Silica, $\text{mg/L}$	1	--	--	9	7.4	--	3.1
TOTAL NITROGEN as N, $\text{mg/L}$	.38	--	.63	.56	.36	--	3.75
ORGANIC NITROGEN as N, $\text{mg/L}$	.21	--	.49	.35	.28	--	.44
AMMONIA NITROGEN as N, $\text{mg/L}$	<.01	--	.01	.01	.01	--	.01
NITRITE as N, $\text{mg/L}$	.04	--	<.01	<.01	<.01	--	.05
NITRATE as N, $\text{mg/L}$	.12	--	.12	.19	.06	--	3.25
Total phosphorus as P, $\text{mg/L}$	.03	--	.02	.02	.03	--	.03
ORTHOPHOSPHORUS as P, $\text{mg/L}$	.01	--	.01	.01	.02	--	.02

Chemical analysis of highway runoff at varying depth intervals from storm 8,  
September 1, 1983, at Pembroke Road

[Constituents shown in capital letters are the most common highway contaminants.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter;  $<$  = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface					Water table
	Swale	0.5	1.0	2.0	6.0	
Barium, $\mu\text{g/L}$	30	76	57	42	16	15
Beryllium, $\mu\text{g/L}$	<.5	<.5	<.5	<.5	<.5	<.5
Cadmium, $\mu\text{g/L}$	<1	<1	<1	<1	<1	<1
CHROMIUM, $\mu\text{g/L}$	<1	--	--	--	<1	<1
Cobalt, $\mu\text{g/L}$	<3	<3	<3	<3	<3	<3
COPPER, $\mu\text{g/L}$	<10	<10	<10	<10	<10	<10
IRON, $\mu\text{g/L}$	72	10	7	5	5	58
LEAD, $\mu\text{g/L}$	20	<10	<10	<10	<10	<10
Lithium, $\mu\text{g/L}$	<4	<4	<4	<4	<4	<4
Manganese, $\mu\text{g/L}$	3	<1	<1	<1	<1	<1
MERCURY, $\mu\text{g/L}$	<.1	.1	.1	<.1	<.1	<.1
Molybdenum, $\mu\text{g/L}$	<10	<10	<10	<10	<10	<10
NICKEL, $\mu\text{g/L}$	1	--	--	1	2	1
Strontium, $\mu\text{g/L}$	80	210	220	450	290	410
Vanadium, $\mu\text{g/L}$	<6	<6	6	<6	6	<6
ZINC, $\mu\text{g/L}$	50	40	4	6	10	34
Calcium, $\text{mg/L}$	19	29	31	63	37	58
Magnesium, $\text{mg/L}$	.41	.45	.6	.23	.33	.55
Hardness, $\text{mg/L}$	49	75	80	160	94	150
Sodium, $\text{mg/L}$	1.1	1.1	1.1	1.1	1	1.9
Silica, $\text{mg/L}$	.58	4.7	7.1	8.4	13	1.5
TOTAL NITROGEN as N, $\text{mg/L}$	.34	--	.24	.17	.44	.45
ORGANIC NITROGEN as N, $\text{mg/L}$	.21	--	.18	.15	.41	.13
AMMONIA NITROGEN as N, $\text{mg/L}$	.01	--	.02	.01	.01	.01
NITRITE as N, $\text{mg/L}$	.03	--	.01	<.01	<.01	<.01
NITRATE as N, $\text{mg/L}$	.09	--	.03	.01	.01	.3
Total phosphorus as P, $\text{mg/L}$	.03	--	.05	.01	.01	.01
ORTHOPHOSPHORUS as P, $\text{mg/L}$	.01	--	.01	<.01	<.01	<.01

Chemical analysis of highway runoff at varying depth intervals from storm 9,  
September 28, 1983, at Dixie water-treatment plant

[Constituents shown in capital letters are the most common highway contaminants. Lysimeter destroyed at the 0.5- and 6.0-foot depths.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter; < = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface						Water table
	Swale	0.5	1.0	2.0	3.0	6.0	
Barium, $\mu\text{g/L}$	20	--	--	--	--	--	11
Beryllium, $\mu\text{g/L}$	<.5	--	--	--	--	--	<.5
Cadmium, $\mu\text{g/L}$	<1	--	--	--	--	--	<1
CHROMIUM, $\mu\text{g/L}$	<1	--	--	--	--	--	<1
Cobalt, $\mu\text{g/L}$	<3	--	--	--	--	--	<3
COPPER, $\mu\text{g/L}$	<10	--	--	--	--	--	<10
IRON, $\mu\text{g/L}$	36	--	--	--	--	--	84
LEAD, $\mu\text{g/L}$	10	--	--	--	--	--	<10
Lithium, $\mu\text{g/L}$	<4	--	--	--	--	--	<4
Manganese, $\mu\text{g/L}$	4	--	--	--	--	--	2
MERCURY, $\mu\text{g/L}$	<.1	--	--	--	--	--	<.1
Molybdenum, $\mu\text{g/L}$	10	--	--	--	--	--	<10
NICKEL, $\mu\text{g/L}$	2	--	--	--	--	--	1
Strontium, $\mu\text{g/L}$	65	--	--	--	--	--	650
Vanadium, $\mu\text{g/L}$	<6	--	--	--	--	--	27
ZINC, $\mu\text{g/L}$	6	--	--	--	--	--	<3
Calcium, $\text{mg/L}$	11	--	--	--	--	--	66
Magnesium, $\text{mg/L}$	.58	--	--	--	--	--	1.3
Hardness, $\text{mg/L}$	30	--	--	--	--	--	170
Sodium, $\text{mg/L}$	4.1	--	--	--	--	--	4.1
Silica, $\text{mg/L}$	.29	--	--	--	--	--	3.5
TOTAL NITROGEN as N, $\text{mg/L}$	.73	--	1.04	0.45	0.38	--	3.49
ORGANIC NITROGEN as N, $\text{mg/L}$	.31	--	.98	.27	.25	--	.48
AMMONIA NITROGEN as N, $\text{mg/L}$	.01	--	.01	.01	.01	--	.01
NITRITE as N, $\text{mg/L}$	.02	--	<.01	.01	.01	--	.04
NITRATE as N, $\text{mg/L}$	.39	--	.04	.16	.11	--	2.96
Total phosphorus as P, $\text{mg/L}$	.02	--	.02	.02	.02	--	.03
ORTHOPHOSPHORUS as P, $\text{mg/L}$	.02	--	.02	.02	.02	--	.03



Chemical analysis of highway runoff at varying depth intervals from storm 9,  
September 28, 1983, at Pembroke Road

[Constituents shown in capital letters are the most common highway contaminants. Lysimeter destroyed at the 1.0-foot depth. Sample volume at 6.0-foot depth too small to analyze for all constituents.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter;  $<$  = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface					Water table
	Swale	0.5	1.0	2.0	6.0	
Barium, $\mu\text{g/L}$	19	--	--	--	--	10
Beryllium, $\mu\text{g/L}$	<.5	--	--	--	--	<.5
Cadmium, $\mu\text{g/L}$	<1	--	--	--	--	<1
CHROMIUM, $\mu\text{g/L}$	18	--	--	--	--	<1
Cobalt, $\mu\text{g/L}$	<3	--	--	--	--	<3
COPPER, $\mu\text{g/L}$	<10	--	--	--	--	<10
IRON, $\mu\text{g/L}$	25	--	--	--	--	38
LEAD, $\mu\text{g/L}$	30	--	--	--	--	<10
Lithium, $\mu\text{g/L}$	<4	--	--	--	--	<4
Manganese, $\mu\text{g/L}$	3	--	--	--	--	2
MERCURY, $\mu\text{g/L}$	<.1	--	--	--	--	<.1
Molybdenum, $\mu\text{g/L}$	<10	--	--	--	--	<10
NICKEL, $\mu\text{g/L}$	1	--	--	--	--	1
Strontium, $\mu\text{g/L}$	41	--	--	--	--	460
Vanadium, $\mu\text{g/L}$	13	--	--	--	--	<6
ZINC, $\mu\text{g/L}$	12	--	--	--	--	<3
Calcium, $\text{mg/L}$	9.8	--	--	--	--	64
Magnesium, $\text{mg/L}$	.57	--	--	--	--	.78
Hardness, $\text{mg/L}$	27	--	--	--	--	160
Sodium, $\text{mg/L}$	3.3	--	--	--	--	2.7
Silica, $\text{mg/L}$	.11	--	--	--	--	1.6
TOTAL NITROGEN as N, mg/L	.59	0.60	--	0.14	--	.52
ORGANIC NITROGEN as N, mg/L	.31	.5	--	.12	--	.19
AMMONIA NITROGEN as N, mg/L	.01	.01	--	.01	0.01	.01
NITRITE as N, $\text{mg/L}$	.01	.01	--	.01	.01	.01
NITRATE as N, $\text{mg/L}$	.26	.08	--	>01	.04	.31
Total phosphorus as P, mg/L	.02	.01	--	.01	--	.01
ORTHOPHOSPHORUS as P, mg/L	.02	.01	--	.01	.03	.01

Chemical analysis of highway runoff at varying depth intervals from  
storm 10, November 3, 1983, at Dixie water-treatment plant

[Constituents shown in capital letters are the most common highway contaminants. Lysimeter destroyed at the 6.0-foot depth. Pt-Co = platinum-cobalt;  $\mu$ S/cm = microSiemens per centimeter; NTU = nephelometric turbidity unit; mg/L = milligram per liter; < = concentration below analytical detection limit; and -- = no data]

Constituent	Depth, feet below land surface						Water table
	Swale	0.5	1.0	2.0	3.0	6.0	
Color, Pt-Co units	30	--	--	--	10	--	40
pH, units	7.9	--	--	--	8.5	--	7.8
Specific conductance, $\mu$ S/cm at 25 °C	245	--	--	--	380	--	325
Turbidity, NTU units	3	--	--	--	1.5	--	1.2
TOTAL NITROGEN as N, mg/L	.55	0.66	0.47	0.31	.44	--	.96
ORGANIC NITROGEN as N, mg/L	.51	.59	.33	.1	.32	--	.2
AMMONIA NITROGEN as N, mg/L	.03	.03	.04	.03	.02	--	.03
NITRITE as N, mg/L	<.01	<.01	<.01	<.01	<.01	--	.05
NITRATE as N, mg/L	.01	.03	.09	.17	.09	--	.68
Total phosphorus as P, mg/L	.02	.09	.09	.06	.03	--	.03
ORTHOPHOSPHORUS as P, mg/L	<.01	.07	.03	.02	.02	--	.02

Chemical analysis of highway runoff at varying depth intervals from  
storm 11, November 16, 1983, at Dixie water-treatment plant

[Constituents shown in capital letters are the most common highway contaminants.  $\mu\text{g/L}$  = microgram per liter; Pt-Co = platinum-cobalt; NTU = nephelometric turbidity unit;  $\text{mg/L}$  = milligram per liter; < = concentration below analytical detection limit; and -- = no data]

Constituent	<u>Total samples</u>		<u>Dissolved samples</u>	
	Swale	Water table	Swale	Water table
Arsenic, $\mu\text{g/L}$	2	1	1	<1
Barium, $\mu\text{g/L}$	--	--	--	--
Beryllium, $\mu\text{g/L}$	--	--	--	--
Cadmium, $\mu\text{g/L}$	40	20	1	<1
CHROMIUM, $\mu\text{g/L}$	150	20	<10	<10
Cobalt, $\mu\text{g/L}$	60	<50	2	2
COPPER, $\mu\text{g/L}$	100	40	13	1
IRON, $\mu\text{g/L}$	4,800	780	40	110
LEAD, $\mu\text{g/L}$	2,100	200	28	<1
Lithium, $\mu\text{g/L}$	--	--	--	--
Manganese, $\mu\text{g/L}$	50	20	<10	<10
MERCURY, $\mu\text{g/L}$	<.1	<.1	<.1	<.1
Molybdenum, $\mu\text{g/L}$	--	--	--	--
NICKEL, $\mu\text{g/L}$	8	1	1	<1
Strontium, $\mu\text{g/L}$	580	530	120	660
Vanadium, $\mu\text{g/L}$	--	--	--	--
ZINC, $\mu\text{g/L}$	580	20	30	20
Color, Pt-Co units	50	20		
pH, units	7	7.2		
Turbidity, NTU units	40	.5		
TOTAL NITROGEN as N, $\text{mg/L}$	1.96	.86	.99	.83
ORGANIC NITROGEN as N, $\text{mg/L}$	1.41	.23	.52	.21
AMMONIA NITROGEN as N, $\text{mg/L}$	.09	.01	.05	.01
NITRITE as N, $\text{mg/L}$	.07	.04	.05	.04
NITRATE as N, $\text{mg/L}$	.39	.58	.37	.57
Total phosphorus as P, $\text{mg/L}$	.3	.02	.08	.02
ORTHOPHOSPHORUS as P, $\text{mg/L}$	.13	.02	.06	.02

Chemical analysis of highway runoff at varying depth intervals from storm 12, November 30, 1983, at Pembroke Road

[Constituents shown in capital letters are the most common highway contaminants.  $\mu\text{g/L}$  = microgram per liter;  $\text{mg/L}$  = milligram per liter; < = concentration below analytical detection limit; and -- = no data]

Constituent	Total samples	
	Swale	Water table
Arsenic, $\mu\text{g/L}$	2	<1
Cadmium, $\mu\text{g/L}$	30	20
CHROMIUM, $\mu\text{g/L}$	40	10
Cobalt, $\mu\text{g/L}$	60	50
COPPER, $\mu\text{g/L}$	50	20
IRON, $\mu\text{g/L}$	4,300	630
LEAD, $\mu\text{g/L}$	1,800	300
Manganese, $\mu\text{g/L}$	70	10
MERCURY, $\mu\text{g/L}$	<.1	<.1
NICKEL, $\mu\text{g/L}$	12	2
Strontium, $\mu\text{g/L}$	350	430
ZINC, $\mu\text{g/L}$	780	10
TOTAL NITROGEN as N, $\text{mg/L}$	4.32	.3
ORGANIC NITROGEN as N, $\text{mg/L}$	3.5	.1
AMMONIA NITROGEN as N, $\text{mg/L}$	.1	.02
NITRITE as N, $\text{mg/L}$	.1	<.01
NITRATE as N, $\text{mg/L}$	.62	.18
Total phosphorus as P, $\text{mg/L}$	.17	.04
ORTHOPHOSPHORUS as P, $\text{mg/L}$	.11	.01